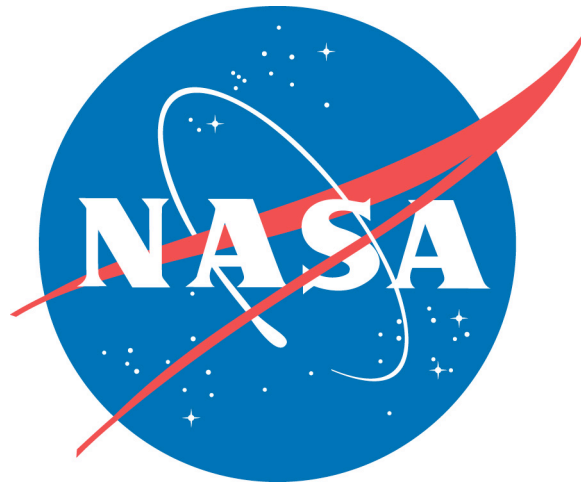


**Benchmark Report for “Integrated forecasting system for mitigating adverse space weather effects on the Northern American high-voltage power transmission system”**

*NASA Goddard Space Flight Center in collaboration with the Electric Power Research Institute*



## Benchmark Report for Solar Shield

### Acknowledgments

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## Executive Summary

The Solar Shield<sup>1</sup> project responds to the NASA Strategic Goal 3, Sub-goal 3A: “Study Earth from space to advance scientific understanding and meet societal needs” as described in the 2006 NASA Strategic Plan. The project is funded by the NASA Applied Sciences Program, which has the objective to expand and accelerate the economic and societal benefits from Earth science, information, and technology. The project is managed within the NASA Applied Sciences Program’s “Weather” program element.

In this project, an enhancement to the Electrical Power Research Institute’s (EPRI) SUNBURST research support tool used by the U.S. electric power industry is developed by prototyping a Geomagnetically Induced Current (GIC) forecasting system for the effects of solar activity on the North American power grid. The forecasting system will consist of a chain of state-of-the-art space physics models describing the coupled Sun-Earth system. Predictions of GIC flowing in the power transmission system are derived from the model chain output and are used to create products for the end-user making decisions about possible GIC mitigation actions.

Models employed by the forecasting system are resident at the Community Coordinated Modeling Center (CCMC) located at the NASA Goddard Space Flight Center in Greenbelt, Maryland. These models, which have been developed using NASA resources by the space research community, have been provided to the CCMC for research simulation and evaluation of space weather applications, such as the one discussed in this document.

The model chain will be driven by solar data from NASA missions such as SOHO, or from ground-based observatories. Additionally, NASA’s ACE spacecraft, which is located upstream from the Earth, will provide a second source of driver data for the magnetosphere/ionosphere component of the model chain.

In this report a) the final design and the real-time implementation of the GIC forecasting system is described in detail and b) the systems engineering and benchmarking activities carried out in the project are documented. The established GIC forecasting system is composed of two partially separate components providing long lead-time Level 1 and short lead-time Level 2 estimates. Two different approaches for verifying and validating the two levels of the system are devised and executed. The integration of the forecasting system to the SUNBURST research support tool has been completed and the real-time forecast validation system is a functional tool for ongoing research activities within EPRI. Further, the impact of GIC on high-voltage power transmission systems has been evaluated from a number of different perspectives. The impact of large GIC was quantified in terms of cost of mitigation actions and benefit of (losses to utilities and to the society) taking mitigation actions if GIC forecasts are available. It is shown that GIC poses a potentially significant threat to the operability of high-voltage transmission systems and that the established forecasting system can be used to control the threat.

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<sup>1</sup> Throughout the text we will, for brevity, refer to the activity as “Solar Shield”.

## 1.0 Introduction

The activity discussed in this document seeks to enhance the capabilities of the Electrical Power Research Institute's (EPRI) SUNBURST research support tool used by the U.S. electric power industry by prototyping a system for forecasting the effects of solar activity on the North American power grid. The enhancements will support ongoing research as activity increases into the next solar cycle. The forecasting system consists of a chain of models, which transmit plasma and magnetic fields and their dynamics from the solar surface and heliosphere, to the magnetosphere of the Earth, and then into the Earth's ionosphere. Geomagnetically Induced Currents (GIC) flowing in the power transmission system and the geoelectric field driving GIC will be derived from these ionospheric currents. By using real-time space-based observations (carried out by NASA) of solar and near-space conditions and the developed model chain, GIC forecasts can be derived to individual sites of the North American power transmission system. These forecasts, together with other real-time information available via SUNBURST network can then be used by operators of the transmission system to mitigate the potentially harmful effects of solar activity on the North American power grid.

The identified two-level system requirements (see *Evaluation Report*, 2008) led to the development of two partly separate forecast products: a) Level 2 product based on in situ Lagrange 1 (L1) point solar wind observations and magnetospheric magnetohydrodynamic (MHD) simulations and b) Level 1 product based on remote solar observations and heliospheric MHD simulations. The implemented real-time system has been running since February 2008. The real-time forecast validation has been operational since September 2009. EPRI carried out an extensive literature survey on the impacts of GIC on high-voltage transmission systems and the analysis indicated a clear correlation between transformer dissolved gasses and GIC, which is indicative of over heating-related and possibly cumulative damage to the transmission system. Further, EPRI carried out a detailed analysis on the economic impact of GIC on high-voltage transmission systems. The analysis is used to show that the generated forecasting system is capable of providing tangible value for the operator of the transmission system.

In this report a) the final design and the real-time implementation of the GIC forecasting system is described in detail and b) the systems engineering and benchmarking activities carried out in the project are documented. The structure of the report is as follows. In Section 2 the systems engineering activities carried out in the project are described. In Section 3 the benchmarking results including the economic impact analysis and updated verification and validation analyses are presented. Section 4 discusses the benchmarking gaps and finally, in Section 5, the general conclusions and recommendations for further improvements are provided. In Appendix A, Solar Shield-related publications published by the team members, presentations and education and public outreach activities are listed. Appendix B documents the full economic impacts analysis carried out by EPRI.

## 2.0 Summary of Systems Engineering Activities

This section details the systems engineering activities carried out in the Solar Shield project. First, the system requirements identified in the beginning of the activity are described. Then the design of the two-level forecasting system and its coupling to the SUNBURST research support tool are described. The established system has been validated both by means of historical GIC

events and a real-time validation process. These validation activities are described in the last two parts of the section.

## System Requirements

By considering the GIC mitigation actions available to the power utilities and the current and near-future space physics modeling capabilities, the Solar Shield team identified the following requirements to be met by the forecasting system:

a) The system should be able to give advance warnings at two different levels: Level 1 warnings providing lead-time of 1-2 days and Level 2 warnings providing lead-time of 30-60 minutes. Level 1 warnings are based on remote sensing information about solar activity whereas Level 2 warnings are based on in situ L1 observations.

b) The system should be able to predict the start time of the GIC activity. Start times are given separately for Level 1 and Level 2 forecasts.

c) The system should be able to predict the intensity of the GIC activity. Intensities are given separately for Level 1 and Level 2 forecasts.

d) The system should be able to indicate the geographic regions or locations affected by the GIC activity. Affected geographic regions are given separately for Level 1 and Level 2 forecasts.

e) The system should be able to predict the end of the GIC activity. End times are given separately for Level 1 and Level 2 forecasts.

f) The system should be able to give uncertainty of the prediction. Uncertainties are given separately for Level 1 and Level 2 forecasts.

g) The system should be able to give the prediction of the GIC activity in a form usable for the decision-making process associated with possible GIC mitigation actions.

The determination of the required minimum accuracy for both the Level 1 and Level 2 forecasts was the fundamental motivation for EPRI's cost-benefit analysis described in detail in Appendix B. As will be shown below, the system does fulfill the minimum requirements, i.e. the system is capable of providing tangible value.

The requirements given above provided the baseline for the system that was developed in the activity. Although the system does not provide explicit uncertainties associated with the Level 2 forecasts, it is concluded, and shown below, that the developed system fulfills the identified system requirements. Consequently, the Solar Shield project can claim success from the systems engineering viewpoint. For more detailed discussion on the system requirements, see *Evaluation Report*, 2008.

## Forecasting System

The identified two-level system requirements described above led to the development of two partly separate forecast products: a) Level 2 product based on in situ Lagrange 1 (L1) point solar wind observations and magnetospheric magnetohydrodynamic (MHD) simulations and b) Level 1 product based on remote solar observations and heliospheric MHD simulations. The major differences between the products are that they are driven with different input observational data and whereas Level 2 GIC forecasts are fully deterministic, Level 1 forecasts are partly probabilistic. The two products are described in detail below. Tables 1 and 2 summarize the NASA data and models used in the forecasting system. It should be noted that some of the models were not developed at NASA but rather by teams whose work has been supported by NASA. The two-level system has been running in real-time since February 2008. The prototype forecasts are generated currently for the two northernmost North American SUNBURST sites. See Section 5 for discussion on the extension of the system to lower latitude locations.

**Table 1.** NASA data products used to drive the GIC forecasting system.

Satellite	Sensors	System Operator	Product	Use in the forecasting system
ACE	MAG, SWEPAM	NASA	Plasma and magnetic field observations at L1.	To drive magnetospheric MHD models used for Level 2 GIC forecasts.
SOHO	MDI, LASCO	NASA/ESA	Solar magnetograms, CME observations.	To drive heliospheric MHD models used for Level 1 GIC forecasts.

**Table 2.** NASA (sponsored) models used in the current implementation of the GIC forecasting system.

Model	Input	Product	Use in the forecasting system
WSA, potential/empirical model of the inner heliosphere.	Solar magnetograms.	Plasma parameters and the magnetic field in the inner heliosphere.	Input to heliospheric MHD model used for Level 1 GIC forecasts.
ENLIL, MHD model of the heliosphere.	Plasma parameters and the magnetic field in the inner heliosphere.	Plasma parameters and the magnetic field in the heliosphere.	Input to the probabilistic model used for Level 1 GIC forecasts.
BATSRUS, MHD model of the magnetosphere-ionosphere system.	Plasma parameters and the magnetic field in the vicinity of the solar wind-magnetosphere boundary.	Plasma parameters and the magnetic field in the magnetosphere. Electrostatic parameters in the ionosphere.	Input to the geomagnetic induction and GIC computations at high latitudes. Used for Level 2 GIC forecasts.

Geomagnetic induction model by A. Pulkkinen.	Ionospheric electric current distribution.	Goelectric field and GIC at given locations.	Provides the final computational output of the forecasting system.
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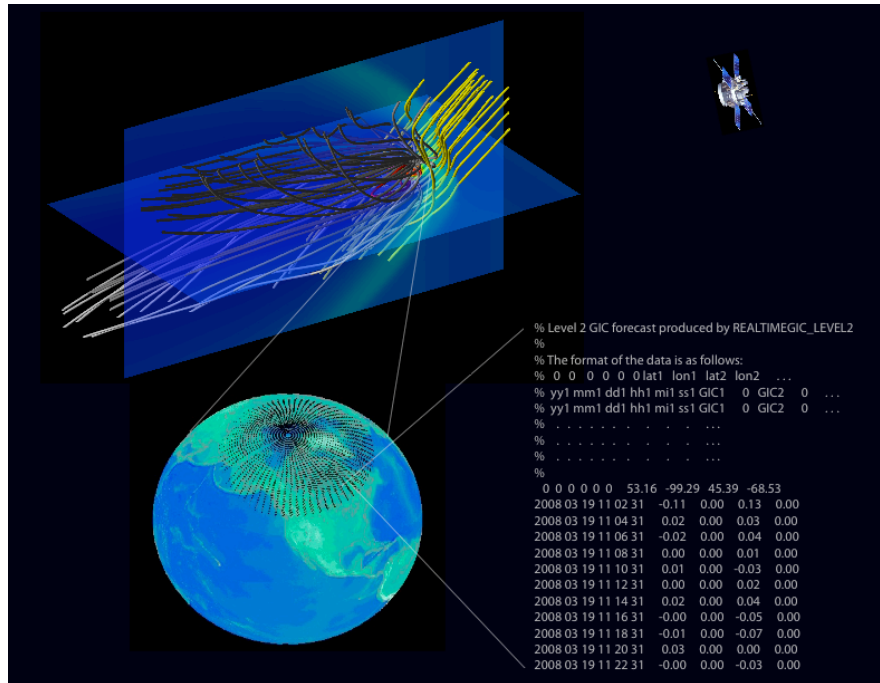
## Level 2 Forecasts

Level 2 GIC forecasts are driven by in situ solar wind observations carried out at the Lagrange 1 point about 1.5 million kilometers upstream of the Earth (Fig. 1). In an ideal case, depending on the structure and the speed of the solar wind, Level 2 forecasts can give 30-60 minute lead-time for the end-user to react. It is noted that although this is a relatively short lead-time, there are some procedures the operator of the transmission system can follow to mitigate the impacts of GIC in less than 60 minutes.

The Lagrange 1 solar wind observations carried out by MAG magnetometer (*Smith et al.*, 1998) and Solar Wind Electron, Proton, and Alpha Monitor (SWEPAM) (*McComas et al.*, 1998) instruments onboard NASA's Advanced Composition Explorer (ACE) are used to drive a global magnetospheric MHD model in real-time. Shortly, MHD describes magnetospheric plasma as a single electrically conducting fluid experiencing not only "regular" forces acting on fluid but also electromagnetic forces. Although this is only approximate description of complex space plasma, MHD successfully reproduces many of the central dynamical features of the magnetosphere.

An important feature of modern magnetospheric MHD models is that they are coupled to ionospheric electrostatic modules. The ionospheric module provides quasi-static description of the spatiotemporal behavior of the ionospheric currents responsible for high-latitude GIC. The connection between the ionospheric MHD output and GIC is established in Solar Shield in two steps (for details see, *Pulkkinen et al.*, 2007a). First, ionospheric currents generated by MHD are used in geomagnetic induction module that will provide the geoelectric field on the surface of the Earth. The geoelectric field is then used to compute GIC at desired location of the individual power transmission system. It should be noted that the two steps are strongly dependent on the local ground conductivity structure and on the electrical and the topological properties, or shortly the system parameters, of the transmission system of interest. Optimal ground conductivity and the system parameters are determined from the geomagnetic field and GIC observations by applying the methods developed by *Pulkkinen et al.* (2007b).





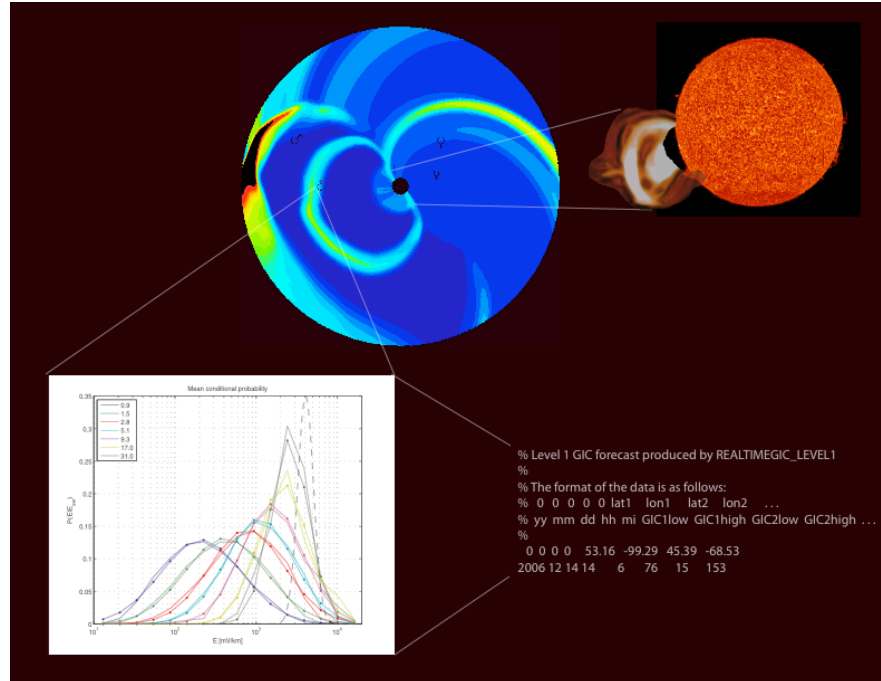
**Fig. 1.** The process used to generate Level 2 GIC forecasts. Lagrange 1 point solar wind observations carried out by ACE are used to drive global magnetospheric MHD model. The ionospheric current output of the MHD model is used to compute GIC at individual power transmission system nodes. The final output of the system is given as a text file, which is provided to EPRI for integration into the SUNBURST research support tool. The MHD, ionospheric current and GIC data shown in the figure are from an actual model run.

The current implementation of the Level 2 forecasts uses real-time Block-Adaptive-Tree-SolarWind-Roe-Upwind-Scheme (BATS-R-US) MHD model (*Powell et al.*, 1999) runs carried out at CCMC. The forecasts generated for individual power transmission system nodes are stored into a text file (see Fig. 1), which is then downloaded for the usage in EPRI's SUNBURST research support tool to be discussed below. In the current setting of the forecasting system Level 2 forecasts are updated every ten minutes.

## Level 1 Forecasts

Although also Level 2 products play an important role in the forecasting system, Level 1 GIC forecasts are, due to the longer lead-time associated with the product, potentially of more importance to the end-user. In principle, one could try to implement Level 1 forecast utilizing all the available information about solar and heliospheric conditions, such as the location and the structure of the high-speed streams originating from the solar coronal holes. However, the economic analysis carried by EPRI (Appendix B) emphasizes the large potential cost associated with extreme GIC events. Thus, the current implementation of the system focuses in forecasting disturbances associated with coronal mass ejections (CMEs), which are to our present understanding the solar events driving the most severe space weather conditions. Depending on

the speed of the approaching CME, Level 1 forecasts can give 1-2 day lead-time for the end-user to react.



**Fig. 2.** The process used to generate the Level 1 GIC forecasts. Solar observations (LASCO instrument onboard the SOHO spacecraft) of CMEs are used to initiate a disturbance at the inner boundary of a heliospheric MHD model that propagates the CME to the Earth. The modeled MHD parameters at the Earth are used in a statistical model coupling solar wind bulk properties to GIC at individual power transmission system nodes. The final output of the system is given as a text file, which is fed into the SUNBURST research support tool. The CME, heliospheric MHD and GIC shown in the figure are real LASCO, ENLIL heliospheric MHD model (ecliptic view) and Level 1 forecast data. Note, however, that the image of the Sun is not produced by LASCO but by Extreme ultraviolet Imaging Telescope (EIT) instrument also onboard SOHO.

The following process is used to generate the Level 1 forecasts (Fig. 2). First, solar observations of CMEs carried out by Large Angle and Spectrometric Coronagraph Experiment (LASCO) instrument (*Brueckner et al.*, 1995) onboard NASA/ESA Solar and Heliospheric Observatory (SOHO) located at the Lagrange 1 point are used to set the parameters of the so-called cone model (*Xie et al.*, 2004). The cone model parameters that approximate CME as a plasma cone are then used to introduce an over-pressured plasma transient at the inner boundary of the ENLIL heliospheric MHD model by *Odstroil and Pizzo* (1999). ENLIL (named after an ancient god of wind) is used to propagate the observed solar disturbance through the ambient solar wind, which in turn is modeled by using synoptic solar magnetograms (*Odstroil et al.*, 2005), to the Earth and the modeled MHD parameters are used to generate an estimate for expected GIC levels. As current heliospheric MHD models are unable to reproduce the fine structure of the turbulent solar wind, probabilistic coupling between the bulk properties of the solar wind and GIC at individual stations is used generate the final Level 1 GIC forecast. The coupling is established by methods developed by *Pulkkinen et al.* (2008) and by using the local ground conductivities and system parameters derived by the methods developed by *Pulkkinen et al.* (2007b). The Level 1 forecasting approach is described in detail in *Pulkkinen et al.* (2009). It

should be noted that, in principle, heliospheric MHD model output could be used as an input to a magnetospheric MHD model that would provide fully first-principles-based estimates for GIC. However, it remains unclear if “smooth” heliospheric MHD output can generate large enough fluctuations in magnetospheric MHD required for large GIC.

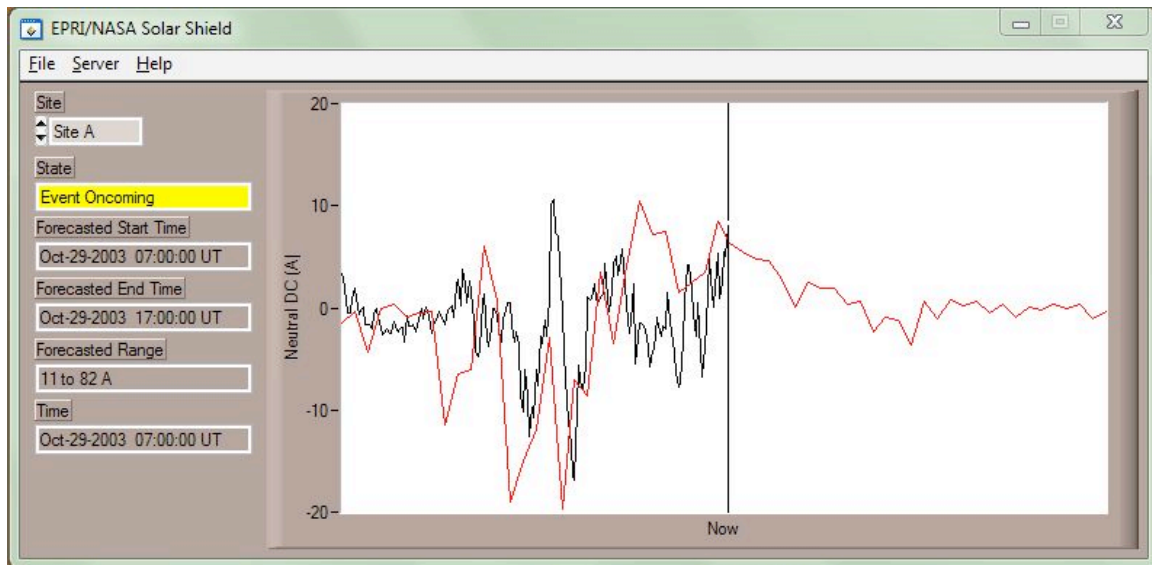
The current implementation of Level 1 forecasts uses ENLIL heliospheric MHD model runs executed at CCMC. The up-to-date ambient solar wind is determined by means of Wang-Sheeley-Arge model (e.g., *Arge et al.*, 2004) and Mount Wilson Observatory synoptic solar magnetograms (*Howard*, 1976). The generated Level 1 GIC forecasts are stored into a text file (see Fig. 2), which is then downloaded for the usage in EPRI’s SUNBURST research support tool. Level 1 forecast is updated every time a new Earth-directed CME has been observed by SOHO/LASCO.

### **Coupling of the Forecasting System to the SUNBURST Research Support Tool**

The value of the raw Level 1 and 2 GIC forecast products is diminished from the end-user viewpoint unless the products are “packaged” in a form that the user can efficiently utilize. The packaging is made in Solar Shield by coupling forecasts to EPRI’s SUNBURST Research Support Tool (RST). As an aftermath of the March 1989 space weather superstorm EPRI launched so-called SUNBURST project, whose primary purpose is to monitor GIC levels in members’ power transmission systems (*Leshner et al.*, 1994). Current SUNBURST RST provides nowcasting of elevated GIC levels and is used by subscribing electric power companies to provide an indication of when and where a potentially damaging GIC event has occurred. The goal of the Solar Shield project was to enhance SUNBURST RST by integrating the Level 1 and Level 2 forecasts into the tool. Meeting this goal required the development of server-side software as well as an end-user interface.

There are two pieces to the server-side Solar Shield software. The purpose of the first part is to include the Solar Shield Level 1 and Level 2 forecast data into the EPRI SUNBURST project database. This database provides central storage of the power system data recorded by the SUNBURST project monitors. Data is recorded on a two second interval, twenty-four hours a day from all of the project member sites. The program downloads the latest forecast files every five minutes from the CCMC’s FTP server. The data is read from these files, reformatted, and inserted into the EPRI SUNBURST database.

The purpose of the second piece of server-side software is to make the data available, via the Internet, to the end-user interface. This program listens for requests from the end-user interface. When a request is received, the latest data available is queried from the database and sent in response.



**Fig. 3:** A screen capture of the Solar Shield end-user interface. The left-hand side of the interface shows the latest Level 1 forecast information. There are four fields included in the Level 1 forecast. The right-hand side of the interface shows the observed GIC and the Level 2 forecast. The vertical bar indicates the time “now”. See the text for a more detailed description of the display.

Fig. 3 shows a screen capture of the final Solar Shield end-user interface. On the left-hand side of Fig. 3, the “State” field tells the user if there is no event, an event is oncoming, or an event is underway. “No event” means there is no GIC activity forecast based on the Level 1 part of the system. “Event oncoming” means that GIC activity has been forecast, but has not started yet. “Event underway” means that GIC activity is occurring.

The field “Forecast Start Time” tells the user the approximate time that the event is expected to start. The “Forecast End Time” tells the user the approximate time the event is expected to end. The “Forecasted Range” field tells the user the range into which the maximum GIC is expected to fall. The “Time” field is the time of the last forecast update. The “Site” field allows the user to select the site for which data is to be viewed.

The right-hand side of the interface shown in Fig. 3 provides the latest Level 2 forecast data as well as the latest observed GIC for the selected site. The plot shows a total of 60 minutes worth of data. The vertical bar shows “now” which is the time of the last query of the database. The black line is the actual GIC data recorded by the monitors at the selected site. The red line is the Level 2 forecast data. The data shown in Fig. 3 contains the actual forecast and observed data for the Halloween storm event of October-November 2003. The end-user interface is designed so that it can be run also for historical events.

The Solar Shield team visited Tennessee Valley Authority (TVA) in Chattanooga, TN in December 10, 2009. One purpose of the visit was to demonstrate the Solar Shield system to TVA. The team demonstrated the system for the October-November 2003 storm event by means of interface in Fig. 3. The TVA response was very encouraging and the team received good feedback for further improvements of the interface. TVA’s high-voltage power transmission system is currently not covered by the Solar Shield system. Extension of the system, discussed more in detail below, is required for generating Level 2 forecasts at low-latitude locations such as TVA.

The visit to TVA served as a first step in the four-step process the Solar Shield team identified for utility-side transition to operations. The steps of the process are:

- 1) Serve past storms to utilities to get feedback on the experimental GIC forecast interface.
- 2) For a real-time storm, work with a non-operations engineer through the whole storm using the experimental interface.
- 3) Longer term hands-off evaluations for real-time storms (still experimental) with non-operational utility engineers.
- 4) If steps 1-3 prove successful identify a roadmap for operational forecasts.

## **V&V Activities**

The GIC forecasting system developed in Solar Shield is enabled by integration of a number of NASA science data products and complex state-of-the-art space physics models (see Tables 1 and 2). Obviously, independent verification and validation (V&V) of individual components of the system was beyond the limited resources of the Solar Shield team. Each instrument and to a large extent each model used in the system have undergone a thorough calibration, V&V etc. carried out by the primary instrument/model teams. These activities are described in the references given above and in *Verification and Validation Report* (2009) when discussing each instrument/model. The Solar Shield team focused on V&V of the end products of the forecasting system, i.e. on V&V of Level 1 and Level 2 forecast outputs. Two different approaches for verifying and validating the two levels of the system were devised and executed for historical storm events. The analyses indicated that despite the difficulties associated with analyzing rare extreme events, both Level 1 and Level 2 forecast accuracies are good enough to have potential for providing tangible value for the user of the forecasting system. V&V activities associated with both products are described in detail in *Verification and Validation Report* (2009). The reader is referred to the V&V report for more details. However, in Section 3 updates based on newly re-evaluated economic analyses along with forecasting system lead-time/availability analyses are provided. Further, V&V implications of the recently finalized Geospace Environment Modeling 2008-2009 Challenge on the forecasting system are discussed in Section 3.

## **Real-time Forecast Validation Tool**

The Solar Shield team recognized that in addition to V&V of the forecasting system using historical events, validation of the actual real-time output from the system is also needed. In fact, it is acknowledged that the evaluation of the true system performance has to be carried out using output from real-time computations as such evaluations take into account, for example, possible sporadic problems with the solar wind driver data, problems with the data transfer and computer crashes that can be controlled in historical analyses. Consequently, although main emphasis was placed on the analysis of historical extreme events not available in the real-time dataset, the Solar Shield team established a real-time Level 2 forecast evaluation tool that continuously monitors the performance of the system. The tool that has been functional since September 2009 is described in detail below. As the Level 1 part of the forecasting system is run

only when there is an observed CME event, continuous monitoring of the performance of this part of the system is not necessary.

The real-time validation tool pulls two data sets (observations and forecasts), automatically populates MySQL tables with the raw data and then calculates validation statistics every hour in near real-time. The Level 2 GIC forecast data product is pulled from the CCMC's FTP server every ten minutes and is used to build the forecast dataset. The observations dataset is pulled from the EPRI SUNBURST server every hour; one-hour segment of data is grabbed from four hours past the present time. The prototype tool developed by the team resides on a secure server at NASA/GSFC. The tool is currently available to the science community at NASA/GSFC.

*Raw data pull.* The raw data for the forecast dataset is archived as text files named with current system time and the process time of the dataset. The Level 2 GIC forecast data product contains 15 data points for intervals of approximately four minutes. Usually the first five data points are in the past, then the next ten are some tens of minutes into the future. These intervals vary depending, for example, on the ACE solar wind driver data availability. EPRI's GIC observations are pulled every hour. Approximately eight records are pulled every hour from four hours past the present time. The EPRI data are the maximum and minimum current in Amperes for 15-minute intervals. In the EPRI data, the minimum can be a negative value since the currents themselves can flow in both positive and negative directions and this information is retained in the data (i.e. no absolute value conversion is made).

*Data alignment.* The two data streams are lined up temporally for analysis. The data values are displayed in Amperes. Absolute values are determined for the performance calculations and graphing. For every 15-minute interval for which one has observed data, the real-time validation tool builds a record for maximum absolute value of the observed and forecasted GIC.

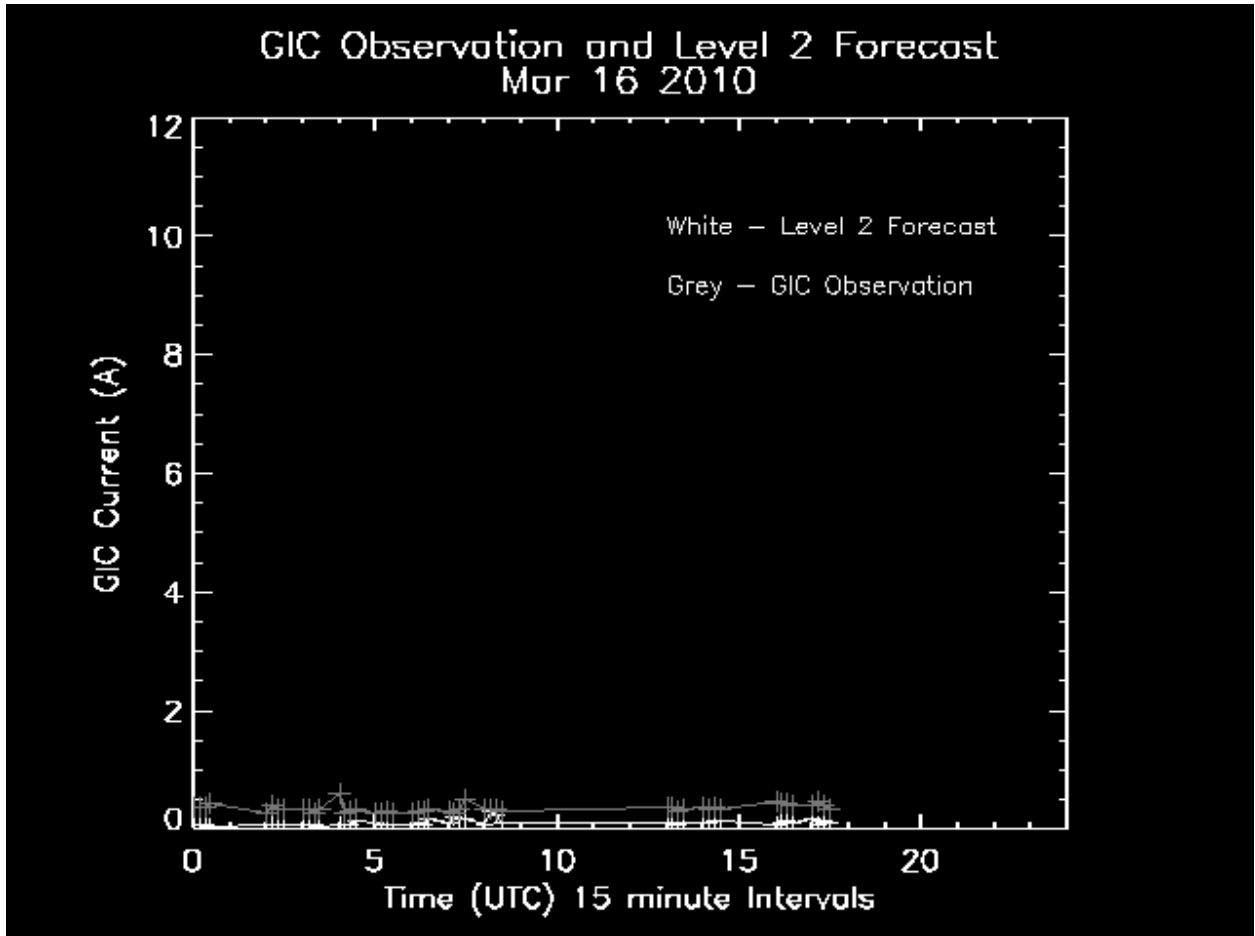
*Calculation of the validation statistics.* Validation statistics are updated every hour. In the first version of the validation tool, two metrics are used to quantify the performance of the system: prediction efficiency and contingency table for forecasted events. Prediction efficiency is defined as

$$PE = 1 - \frac{\langle (|GIC|_{obs} - |GIC|_{mod})^2 \rangle}{\sigma_{obs}^2} \quad (1)$$

where  $\langle \dots \rangle$  indicates arithmetic mean over the time series and  $\sigma_{obs}^2$  indicates the variance of the observed signal. In the current version of the tool,  $PE$  is computed over the length of the entire dataset. In building the contingency table, events are counted for six different thresholds (currently 0.5, 1, 2, 3, 4 and 10 Amperes). It is recognized that GIC events in the 10-100 Ampere range are the threshold between minor and moderate events (see Appendix B). However, lower thresholds are used currently due to the lack of any significant solar activity. Thresholds can be easily adjusted as the solar activity starts to pick up. The contingency tables are built by analyzing the data in 60-minute long non-overlapping windows. For more details on the threshold-based validation and the construction of contingency tables, see *Pulkkinen et al. (2007a)* and *Verification and Validation Report (2009)*.

Figs. 4-6 show three views of the real-time validation tool. Each view is built separately for different sites. As was mentioned above, forecast data is currently available for two of EPRI's North American SUNBURST sites. Fig. 4 shows the line plot that compares observed

and forecasted GIC in a daily plot for the current day. The plot is updated as the day progresses. The daily plot is associated with a web-based comparison table (not shown) that is populated every hour with the observed and forecasted GIC data. No record is built unless observational data is available. However, records are built also in the absence of forecasted data.



**Fig. 4:** Comparison between the forecasted and observed GIC. Both the observed and the forecasted GIC have been during the Solar Shield project essentially in the background noise level (GIC < 1 Amperes) due to the solar minimum conditions. See the text for details.

Fig. 5 shows a web view to the calendar of links to the daily plots that are built at the end of each day. The real-time validation tool automatically builds the plots and the graphic files that can be accessed by clicking the day of interest in the calendar. The “month and year” links display all files built for the station in the corresponding month. Additional data comparison views for the month can be found in these files.

Solar Shield Project  
Station 1 Validation of GIC Forecast  
View Daily Plots for Past Days

<a href="#">December 2009</a>						
Sun	Mon	Tue	Wed	Thu	Fri	Sat
		1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	<a href="#">17</a>	<a href="#">18</a>	<a href="#">19</a>
<a href="#">20</a>	<a href="#">21</a>	<a href="#">22</a>	<a href="#">23</a>	<a href="#">24</a>	<a href="#">25</a>	<a href="#">26</a>
<a href="#">27</a>	<a href="#">28</a>	<a href="#">29</a>	<a href="#">30</a>	<a href="#">31</a>		
<a href="#">January 2010</a>						
Sun	Mon	Tue	Wed	Thu	Fri	Sat
					<a href="#">1</a>	<a href="#">2</a>
<a href="#">3</a>	<a href="#">4</a>	<a href="#">5</a>	<a href="#">6</a>	<a href="#">7</a>	<a href="#">8</a>	<a href="#">9</a>
<a href="#">10</a>	<a href="#">11</a>	<a href="#">12</a>	<a href="#">13</a>	<a href="#">14</a>	<a href="#">15</a>	<a href="#">16</a>
<a href="#">17</a>	<a href="#">18</a>	<a href="#">19</a>	<a href="#">20</a>	<a href="#">21</a>	<a href="#">22</a>	<a href="#">23</a>
<a href="#">24</a>	<a href="#">25</a>	<a href="#">26</a>	<a href="#">27</a>	<a href="#">28</a>	<a href="#">29</a>	<a href="#">30</a>
<a href="#">31</a>						
<a href="#">February 2010</a>						
Sun	Mon	Tue	Wed	Thu	Fri	Sat
	1	2	3	4	5	6
7	8	9	10	11	12	13
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28						
<a href="#">March 2010</a>						
Sun	Mon	Tue	Wed	Thu	Fri	Sat
	1	2	3	4	5	6
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21	22	23	24	25	26	27
28	29	30	31			

**Fig. 5:** Web view to the calendar containing daily comparison plots for the observed and forecasted GIC. See the text for details.

Fig. 6 shows the most current forecast validation statistics containing information about prediction efficiency defined by Eq. (1) and the event-based analyses (i.e. contingency tables). The tables include counts for the entire dataset for six different thresholds (0.5, 1, 2, 3, 4, 10 Amperes). In the tables, *Hits* – the number of 60-minute long intervals where both the observations and the forecasts were above the given threshold, *Misses* – the number of intervals where the observations were above the threshold but the forecasts were not, *False Alarms* – the number of intervals where the observations were not above the threshold but the forecasts were above the threshold, *Total Number of Events* – the number of intervals where either the observations or the forecasts were above the threshold, *Total Number of Non Event Intervals* – the number of intervals where neither the observations nor the forecasts were above the threshold and *Total Number of Intervals* – the number of 60-minute long intervals in the entire dataset.



Solar Shield Project - Station 1  
Cumulative Validation of GIC Forecast Since 2009 December 17

Prediction Efficiency -1.76260

Recalculated every hour

Maximum Absolute value of GICurrent Measurements in Amps for 60 minute Intervals

Results for 0.5 Amps Threshold

Hits: 3  
Misses: 208  
False Alarms: 6  
Total Number of Events: 217  
Total Number of Non Event Intervals: 1073  
Total Number of Intervals: 1855

Results for 1 Amps Threshold

Hits: 2  
Misses: 35  
False Alarms: 0  
Total Number of Events: 37  
Total Number of Non Event Intervals: 1074  
Total Number of Intervals: 1855

Results for 2 Amps Threshold

Hits: 0  
Misses: 7  
False Alarms: 0  
Total Number of Events: 7  
Total Number of Non Event Intervals: 1076  
Total Number of Intervals: 1855

**Fig. 6:** Web view of the validation statistics. Only event thresholds up to 2 Amperes are shown. See the text for details.

It is emphasized that both the observed and the forecasted GIC have been essentially at the background noise level since the launch of the system in February 2008. The low GIC levels are due to the current solar minimum conditions. Consequently, the real-time validation tool and the real-time forecasting system performance remain to be tested for actual significant GIC events. The next solar maximum is expected to occur about year 2013. Large GIC events, however, are expected to occur also before the solar maximum conditions.

### 3.0 Benchmarking

In this section the GIC impacts are benchmarked in terms of study of transformer dissolved gasses and economic impact on high-voltage power transmission system operations. The cost-benefit results of the economic analysis will be used to indicate that the established forecasting system can be used to seek for tangible value. Further, updates on the V&V studies discussed in Section 2 are provided and implications of the recent community-wide geospace modeling challenge for the Solar Shield project are discussed.

## Study on the Impact of GIC on Transformer Dissolved Gas Analysis

The failures of high-voltage power transmission systems during strong space weather storms or geomagnetic disturbances (GMD) are well documented in the literature and the typical modes of failure are fairly well known (see, e.g., *Bolduc, 2002; Molinski, 2002; Pulkkinen et al., 2005*). If a transformer fails during a GMD, there is a clear and strong correlation between the two events. It is, however, possible that even if a transformer did not fail during the GMD, it did incur some internal damage that can accumulate over number of storm periods and lead to premature failure later in the transformer's life. The internal damage due to GMD leading to possibly delayed problems in operating the transmission system is a poorly studied topic and the Solar Shield team decided that further light should be shed on the issue.

The mechanism through which transformers are damaged during a GMD is localized internal heating due to stray flux. One possible symptom of overheating in a transformer is the generation of gasses that get dissolved within the transformer oil. These dissolved gasses can be analyzed to determine whether overheating did occur during a GMD. This type of oil analysis is very common for large power transformers – and is in fact one of the most useful and most widely used condition assessment techniques. The technique is commonly called DGA (Dissolved Gas Analysis) and the technique is sensitive to a wide range of malfunctions, both thermal and electrical, which in some cases could eventually lead to failure of a transformer if corrective measures are not taken. For off-line testing, sampling intervals are typically from 6 months to 3 years depending on the size and voltage of the transformer; with more frequent sampling for large, critical units and less frequent sampling for smaller, less critical units. With on-line testing, samples are taken and analyzed in time intervals of hours or even less.

A literature study was performed to document cases where DGA samples were taken during (or shortly after) a GMD and a positive correlation were found. Different gasses are produced by different types of faults (electrical, thermal). Since the stray flux results in overheating, the key correlation that is sought is a change in the specific gasses produced by overheating. The change could either be a single step increase – indicating overheating due to stray flux only during the storm itself, or a step increase followed by a further steady increase indicating that an area of damage was created that is severe enough to continue to overheat even after the stray flux is removed. The results of this literature survey are shown below in the Table 3.

**Table 3.** Published cases that were found to show a correlation of DGA with GMDs.

Utility	Date	Status	Reference
Eskom, South Africa	October-November 2003	On a number of GSUs (Generator Step-up Units), correlations have been documented between GMDs, DGA results and failures shortly after the October-November 2003 storm. In some cases these findings have been further validated through internal inspections of the transformers.	Gaunt, C.T., Coetzee, G., Transformer failures in regions incorrectly considered to have low GIC-risk, Dept. of Electr. Eng., Univ. of Cape Town, Cape Town . Power Tech, 2007 IEEE Lausanne, p. 807 – 812.  Thompson,A.W.P. et al, Present day challenges in understanding the geomagnetic hazard to national power grid, J.Adv. Space Res. (2010), doi: 10.1016/j.asr2009.11.023.
Scottish Power, UK	April 2000	Documented DGA correlations using an on-line gas detection sensor (a Hydran) during April 2000 storm. Scottish Power measured the neutral currents during the same time period and was thus able to establish the correlation.	T.H. Breckenridge, T. Cumming, J. Merron, Geomagnetically Induced Current Detection and Monitoring, Developments in Power System Protection, Conference Publication No. 479 0 IEE 2001.
PSE&G, USA	March 1989	Documented DGA correlations with a GMD. An online DGA system (Syprotec) indicated ethane and methane gassing in the unit.	A. Núñez, R.K. Miller, B. Ward, Reduction of failure risk in power transformers through the detection and location of incipient faults using acoustic emission, TECHCON 2003 North America, Orlando, Florida, February 2003.  Wrubel, J.N., Monitoring for Geomagnetically Induced Current Flow Effects using Existing EMS Telemetry, Power Industry Computer Application Conference, 1991, p. 45 – 49, May 7-10, 1991, Baltimore, MD, USA.

The geomagnetic storms in Table 3 are all major space weather events known to cause various problems for operating technological systems both in space and on the ground. Consequently, the literature study demonstrates a good correlation between DGA and GMD for strong storms. Consequently, strong storms can cause internal damage and impact the lifetime of the transformers. However, the impact of small to moderate space weather storms or GMDs is still an open question. The Solar Shield team thus strongly recommends further studies on the correlation between GMDs and DGA.

### **Economic Aspects of Space Weather Impact on the High-Voltage Power Transmission Power Grid**

One of the major goals of the Solar Shield project was to quantify the impact of space weather storms on high-voltage power transmission systems. This is one of the interesting aspects of the project, as the economic impact of space weather and the value of the space weather-related products are important and generally poorly understood subjects (Lanzerotti, 2008). To achieve the goal, EPRI carried out an analysis of the economic impact of different levels of GIC on high-voltage power transmission systems. The analysis, which studied impacts on a representative model power grid emphasizes the special role of extreme GIC events. More specifically, the study indicated a steep power-law type increase in economic cost of the damages as a function of increasing GIC level; while for low levels of GIC the forecasting system may not be able to provide economic benefit, for extreme events capable of generating losses measured in tens of billions of dollars the forecasting system and the associated mitigation actions may provide a major benefit. From the metrics viewpoint, the economic analysis provided the cost-benefit curve that is used in the evaluation of the system (see *Verification and Validation Report*, 2009).

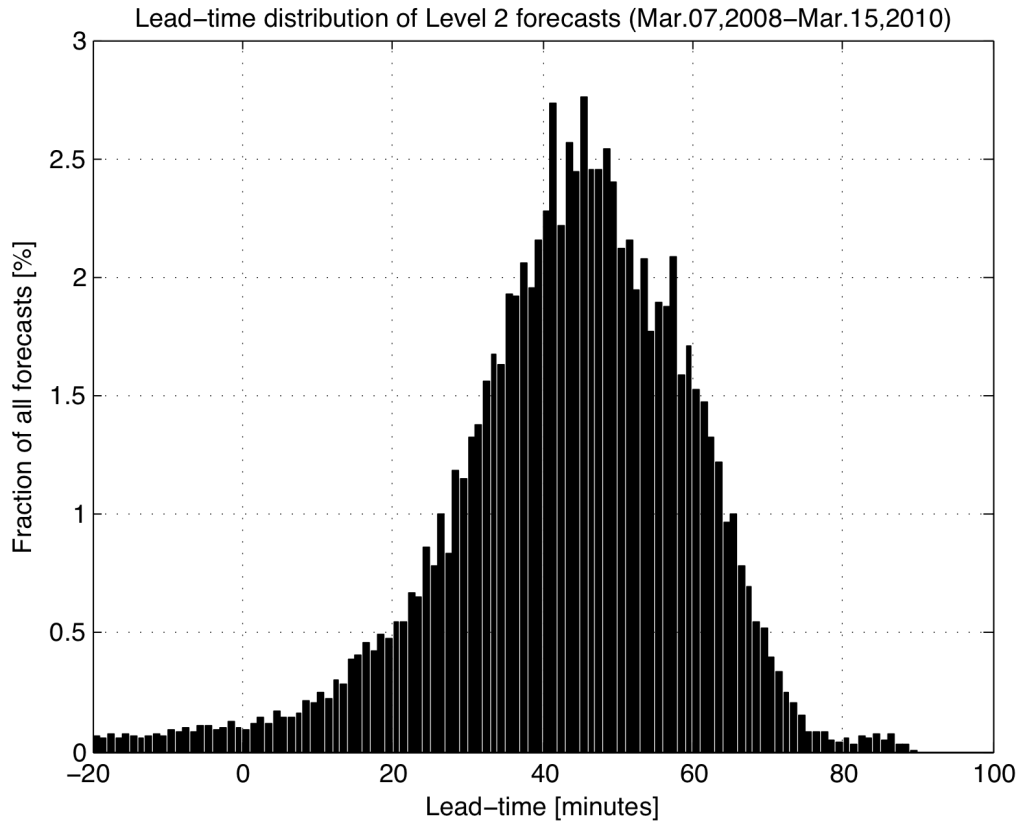
Appendix B documents the full economic analysis carried out by EPRI. The updated cost-benefit numbers not yet included in *Verification and Validation Report* (2009) are used below to revise the earlier V&V analyses.

## Updated V&V Results

One of the central verification/benchmarking questions is whether the forecasting system models the evolution of space weather faster than the actual physical evolution of the system. In another words, does the forecasting system provide positive lead-times? The Solar Shield team has studied the question since the launch of the forecasting system. Fig. 7 shows the lead-time distribution integrated since March 7, 2008. The lead-time is defined as the difference between the last time stamp in the forecast and “now” given by the computer in which the Level 2 forecast file is generated. As one can see, the bulk of the distribution is located between about 20-70 minutes, which is fairly close to the optimal situation given the 44 processors of the Beowulf cluster supercomputer dedicated for the Level 2 system. Due to the missing real-time solar wind data, the model needs sometimes to “catch up”, which causes the negative lead-times. More robust plasma and magnetic field instrument performance and a more reliable data transfer path from the ACE spacecraft to CCMC’s computers would likely prevent most of the negative lead-times seen in Fig. 7. It should be noted that the small secondary distribution having lead-times above 80 minutes is likely an artifact caused by short-duration isolated problems with the accuracy of the clock on the computer in which the Level 2 forecast file is generated.

Once remote solar observations are used to process and launch a CME into the ENLIL model, propagating the disturbance to the Earth’s orbit takes about 2-3 hours. This clearly is substantially faster than the physical propagation of the transient, which takes typically 1-2 days. Consequently, provided that timely remote solar observations are available, Level 1 part of the forecasting system is capable of providing true lead-

times of 1-2 days.

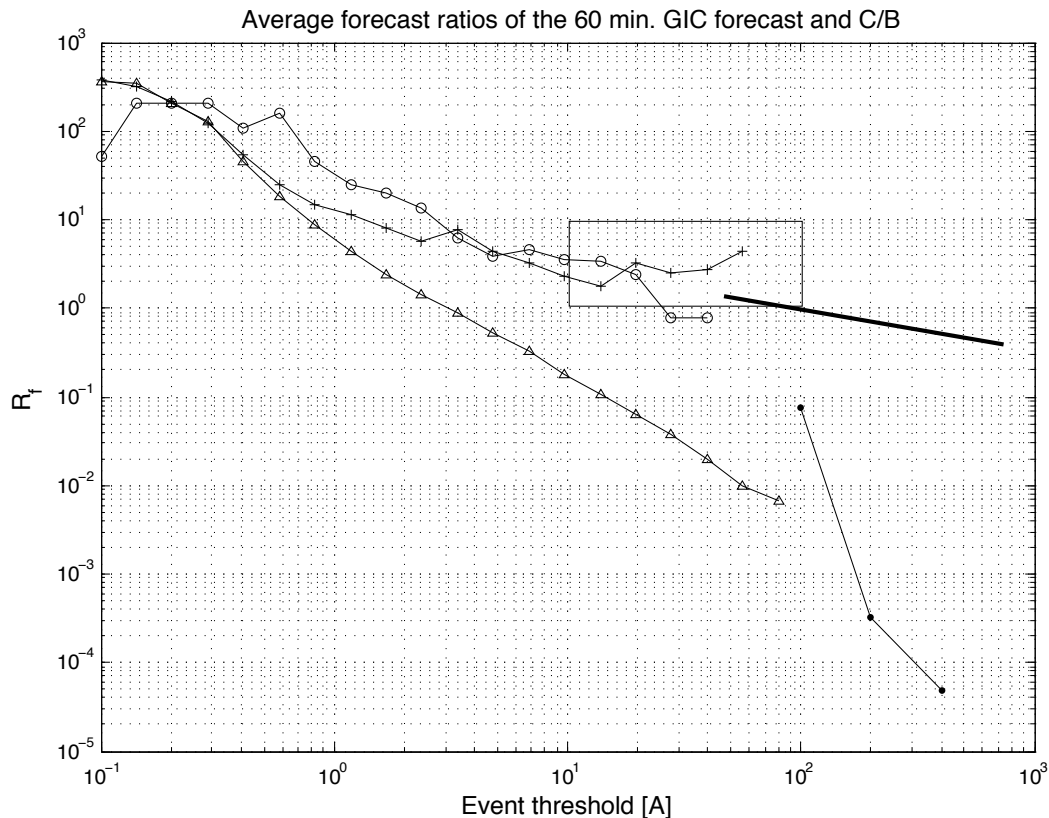


**Fig. 7:** Lead-time distribution of the Level 2 forecasts. Lead-time is the difference between the last time stamp in the forecast and “now”. The distribution has been integrated since March 7, 2008.

In the following, an update to the results in *Verification and Validation Report* (2009) is provided. EPRI’s reanalysis of the economic impact of major GIC events modified the cost-benefit results slightly, which changes the results presented in Fig. 5 of *Verification and Validation Report* (2009).

An updated quantitative view to the system's capabilities is shown in Fig. 8 where forecast ratios of 60-minute forecasts for different model setups are shown along with the final cost-benefit curve (see Appendix B). It is noted that only the costs to the utility were used in generating the cost-benefit curve (societal losses are even higher). The analysis was carried out by using the modeled and observed geomagnetic data (used to compute GIC) for the period of October 24-November, 1, 2003 (for details on the method, see *Pulkkinen et al., 2007a; Verification and Validation Report, 2009*), which was one of the stormiest periods on record. Note that only a subset, including the best performing model, of the forecast ratios associated with different model runs carried out at CCMC are shown. For a reference, Fig. 8 shows also forecast ratio associated with the persistence model that assumes "always alarm on situation", i.e. the model always predicts an event for all GIC levels.

From Fig. 8 a number of important observations can be made. First, it is observed that there are significant differences between different models and model setups used to drive the Level 2 GIC forecasts: for example, higher spatial resolution simulations provide larger and more realistic amplitudes of GIC. Further, the global MHD model-based forecasts can perform significantly better in comparison to simple persistence models. The most important observations, however, concern the relation between the cost-benefit curve  $C/B$  and the forecast ratios. First, it is seen that there is a gap in terms of range of GIC magnitudes between the two. This underscores the difficulty in evaluating the performance of the system for extreme cases: the statistics for rare events are poor and extrapolation is needed to evaluate the performance for the most extreme situations. However, as can be seen from Fig. 8, a rough extrapolation of the forecast ratios of the best performing models to higher GIC magnitudes indicates that the condition for the forecasting system to generate tangible value, i.e. forecast ratios are greater than  $C/B$  (for details, see *Verification and Validation Report, 2009*), holds for extreme GIC events. This in turn indicates that the forecasting system can be used to generate tangible value for the utility. It is emphasized that due to the steepness of the cost-benefit curve, even more conservative extrapolations would fulfill the tangible value condition for the most extreme cases.



**Fig. 8:** The forecast ratio  $R_f$  obtained by using 60 minute-long Level 2 forecast windows. Plusses:  $R_f$  associated with the high spatial resolution BATS-R-US, circles:  $R_f$  associated with the low spatial resolution BATS-R-US, triangles:  $R_f$  associated with the persistence model. The box indicates the approximate  $R_f$  associated with the Level 1 forecasts. The dots indicate the cost-benefit curve obtained from EPRI's economic analysis of large GIC events. The thick line indicates a rough extrapolation of  $R_f$  associated with the best performing models to larger GIC event magnitudes. See the text and *Verification and Validation Report* (2009) for details.

## Implications of the Geospace Environment Modeling 2008-2009 Challenge for the Forecasting System

The Geospace Environment Modeling (GEM) community has recognized that due to the maturity and the increasing complexity of the state-of-the-art global space weather models, there is a great need for a systematic and quantitative evaluation of different geospace circulation modeling approaches. To respond to the need, GEM Global Geospace Circulation Modeling (GGCM) Metrics and Validation Focus Group organized a modeling Challenge focusing on the inner magnetospheric dynamics and ground magnetic field perturbations. The new activity followed the series of earlier GEM Challenges. The 2008-2009 Challenge is a natural next step to GEM efforts as instead of ionospheric convection or isolated substorm events, full storm events containing great

variety of different geospace states were studied. Further, to facilitate unambiguous and objective interpretation of the Challenge results, a particular focus was placed on systematic metrics-based analyses. The primary goals of the evaluations carried out in the 2008-2009 Challenge were to address differences between various modeling approaches, evaluate the current state of GGCM models, demonstrate effects of model coupling and grid resolution, encourage collaborations, and facilitate further model improvements.

The Challenge was initiated at the summer GEM workshop 2008 in Midway, Utah and announced in September 2008. The submissions were made via Community Coordinated Modeling Center's (CCMC) online submission system, which also enables online model comparisons (see <http://ccmc.gsfc.nasa.gov>). Further, a number of model submissions were generated via CCMC's runs-on-request system. The corresponding simulations are publicly available for analysis via CCMC's visualization interface.

Metrics designed to measure models capability to predict GIC were of central interest in the Challenge. Consequently, the Challenge has important implications for the Level 2 forecasting part of the Solar Shield project. More specifically, log-spectral distance measuring models capability to generate GIC-related ground magnetic field fluctuations was one of the four metrics used to quantify the model performance (for details, see *Pulkkinen et al.*, 2010). Altogether thirteen different model submissions were received in the Challenge. Only high-latitude ground magnetic field observations were used in the Challenge.

The two most important implications for the Solar Shield project obtained by applying the log-spectral distance with the thirteen different model predictions are the following. First, it was clear that while for some other metrics empirical models ranked to the top, the physics-based models outperformed the empirical models in terms of the log-spectral distance. This is a clear indication that the state-of-the-art physics-based models are the preferred choice for the Level 2 part of the forecasting system. Second, log-spectral distance-based analyses clearly indicated that increase of the global MHD model spatial resolution and inclusion of inner magnetospheric dynamics into the modeling chain improved the model performance. This is an encouraging result because inclusion of the inner magnetospheric models is necessary for extending the Level 2 part of the forecasting system to lower than about 60 degrees of geomagnetic latitude; possible future inclusion of the inner magnetospheric dynamics does not hamper the high-latitude forecasts. Further, increasing the global MHD spatial resolution is a fairly straightforward way to improve the forecasting system performance given that the required computational resources are readily available. For details on the Challenge and more in depth discussion of the results, see *Pulkkinen et al.* (2010).

## 4.0 Benchmarking Gaps

The DGA literature survey carried out in the Solar Shield project indicated a clear correlation between the high-voltage power transformer gassing and GIC during strong space weather storms. It is of significant interest to expand the study to cover also moderate storms. Such analysis may indicate that also moderate storms can impact the performance of the power transmission system, for example, in terms of “loss-of-life” of the transformers. This action may be assisted by the fact that more and more utilities



monitor DGA on-line and hence have a greater probability of being able to gather DGA data during and after a storm.

As was noted above, statistical analysis of rare extreme cases poses a challenge. More specifically, extrapolation was necessary to analyze the data in Fig. 8. Obviously, the extrapolation is subject to uncertainties that are not easy to assess. The only rigorous approach to overcome the shortcoming is to repeat the analysis once more data from extreme storm events has been accumulated. Further, the true evaluation of the forecasting system performance should be done by using the real-time validation tool developed in the project. However, due to the current solar minimum conditions no significant space weather storms have occurred since the launch of the system in February 2008. The next solar maximum is expected to occur around 2013.

In the analysis of the Level 2 forecasts, the global MHD model output was saved only every four minutes thus dictating the temporal resolution associated with the analysis. As a rule of a thumb, one-minute data should be used in GIC analyses to capture the fluctuations associated with the highest frequencies of the phenomenon. However, saving 1-minute output from a large number of global MHD runs requires vast amounts of disc space, which was not available for the Solar Shield team. However, it is argued that the central V&V results are not significantly impacted by this deficiency. Further, in the GEM 2008-2009 Challenge in which the computational and the storage burden was shared among various research groups, one-minute global MHD output was used. Analyses indicated that the state-of-the-art physics-based models are able to generate the ground magnetic field (and thus GIC) fluctuations also in the times scales of 1-minute.

## 5.0 Conclusions and Recommendations

In this activity, an enhancement to the Electrical Power Research Institute's SUNBURST research support tool used by the U.S. electric power industry was developed by prototyping a system for forecasting the effects of solar activity on the North American power grid. The system will be used by EPRI as a tool for ongoing research. The forecasting system consists of a chain of models, which transmit plasma and magnetic fields and their dynamics from the solar surface and heliosphere, to the magnetosphere of the Earth, and then into the Earth's ionosphere. GIC flowing in the power transmission system and the geoelectric field driving GIC is derived from these ionospheric currents. By using real-time space-based observations of solar and near-space conditions and the developed model chain, GIC forecasts can be derived for individual sites of the North American power transmission system. These forecasts, together with other real-time information available via SUNBURST network, will be used to continue research throughout the next solar cycle. Based on the research results, the long-term vision is for appropriate entities to provide forecasting to operators of the transmission system for mitigating the potentially harmful effects of the solar activity on the North American grid.

In this report a) the final design and the real-time implementation of the GIC forecasting system was described in detail and b) the systems engineering and benchmarking activities carried out in the project were documented. The established GIC forecasting system is composed of two partially separate components providing long

lead-time Level 1 (1-2 days) and short lead-time Level 2 (30-60 minutes) estimates. Two different approaches for verifying and validating the two levels of the system were devised and executed. The analyses that included a comprehensive economic analysis of the GIC impacts indicated that despite the difficulties associated with analyzing rare extreme events, both Level 1 and Level 2 forecast accuracies are good enough to have potential for providing tangible value for the user of the forecasting system.

It can be argued that the experimental forecasting system developed in the Solar Shield project has had a significant impact in the field of space weather. Not only is the Level 2 part of the system the first of a kind to generate fully first-principles-based GIC forecasts but the Level 1 part is the first system utilizing the emerging CME and heliospheric modeling capability for tailored long lead-time forecasts. From the NASA viewpoint, the Solar Shield project is one of the prime examples on how NASA heliophysics data and models can be used for societal benefit. On the other hand, from the EPRI viewpoint, the project has shown the great utility of the SUNBURST GIC dataset, which played a critical role in building and validating the forecasting system. However, despite the great success of the Solar Shield project, the team has recognized a number of issues that need to be addressed to further improve the potential utility of the forecasting system. These issues are discussed in terms of the team recommendations below.

It is noted that while the generated forecasting system meets the basic requirements identified in *Evaluation Report* (2008) (see also Section 2), the global MHD-based approach to Level 2 forecasts is applicable only for high-latitude locations (for more detailed discussion on this, see *Pulkkinen et al.*, 2007a). Thus, the Solar Shield team strongly recommends further studies on possible usage of the state-of-the-art kinetic inner magnetospheric models in Level 2 forecasts that would provide information also about lower latitude GIC. As the current output from the modeling chain is restricted to above about 60 degrees of geomagnetic latitude, the extension of the forecasting system to cover lower latitudes is critical for the application of the Level 2 approach to the US power grid.

As was explained above, the DGA literature survey carried out in the Solar Shield project indicated a clear correlation between the high-voltage power transformer gassing and GIC during strong space weather storms. However, it is of significant interest to expand the study to cover also moderate storms. Such analysis may indicate that also moderate storms can impact the performance of the power transmission system, for example, in terms of “loss-of-life” of the transformers. The Solar Shield team thus recommends further studies on the correlation between DGA and space weather.

Both Level 1 and Level 2 parts are dependent on the solar wind plasma, magnetic field and remote solar (coronagraph) observations provided by aging NASA and NASA/ESA spacecraft: ACE and SOHO. There are no definite plans for the replacement of the observational capabilities provided by these two originally scientific missions and the team sees it critical to establish operational capacity providing robust streams of in situ solar wind and remote solar data. It is emphasized that the recently launched NASA Solar Dynamics Observatory does not have a coronagraph, which is used in the Level 1 part of the forecasting system.

Finally, as noted above, the SUNBURST GIC dataset played a central role in the establishment of the forecasting system. In fact, the forecasts can be generated only to the

sites that have on-line neutral current monitors installed. Installation of new GIC monitoring sites especially to the continental US would enable expansion and increased utility of the newly developed GIC forecasting system.

## 6.0 References

Arge, C.N., J.G. Luhmann, D. Odstrcil, C.J. Schrijver, and Y. Li, Stream structure and coronal sources of the solar wind during the May 12th, 1997 CME, *Journal of Atmospheric and Solar-Terrestrial Physics*, 66, 1295-1309, 2004.

Bolduc, L., GIC observations and studies in the Hydro-Québec power system, *Journal of Atmospheric and Solar-Terrestrial Physics*, Vol. 64, No. 16, 1793-1802, 2002.

Brueckner, E., R. A. Howard, M. J. Koomen, C. M. Korendyke, D. J. Michels, J. D. Moses, D. G. Socker, K. P. Dere, P. L. Lamy, A. Llebaria, M. V. Bout, R. Schwenn, G. M. Simnett, D. K. Bedford, and C. J. Eyles, The Large Angle Spectroscopic Coronagraph (LASCO), *Solar Physics*, 162, 357-402, 1995.

Evaluation Report for “Integrated forecasting system for mitigating adverse space weather effects on the Northern American high-voltage power transmission system”, *NASA Applied Sciences Program report*, 2008.

Lanzerotti, L. J., Economic Impacts of Space Weather, *Space Weather*, 6, S01002, doi:10.1029/2007SW000385, 2008.

Howard, R., The Mount Wilson Solar Magnetograph: Scanning and Data System, *Solar Physics*, 48, 411-416, 1976.

Leshner, R.L., J.W. Porter, and R.T. Byerly, SUNBURST-a network of GIC monitoring systems, *IEEE Transactions on Power Delivery*, Vol. 9, No. 1, January 1994, 128-137, 1994.

McComas, and S.J. Bame, P. Barker, W.C. Feldman, J.L. Phillips, P. Riley, and J.W. Griffiee, Solar Wind Electron Proton Alpha Monitor (SWEPAM) for the Advanced Composition Explorer, *Space Science Reviews*, 86, 563–612, 1998.

Molinski, T., Why utilities respect geomagnetically induced currents, *J. Atmos. Sol-Terr. Phy.*, 64, 1765, 2002.

Odstrcil, D., and V. J. Pizzo, Distortion of the interplanetary magnetic field by three-dimensional propagation of coronal mass ejections in a structured solar wind, *J. Geophys. Res.*, 104(A12), 28225-28240, 10.1029/1999JA900319, 1999.

Odstreil D., V. J. Pizzo, and C. N. Arge, Propagation of the 12 May 1997 interplanetary coronal mass ejection in evolving solar wind structures, *J. Geophys. Res.*, 110, A02106, doi:10.1029/2004JA010745, 2005.

Powell, K. G., Roe, P. L., Linde, T. J., Gombosi, T. I., and De Zeeuw, D. L., A solution-adaptive upwind scheme for ideal magnetohydrodynamics, *J. Comput. Phys.*, 154(2), 284, doi:10.1006/jcph.1999.6299, 1999.

Pulkkinen, A., S. Lindahl, A. Viljanen, and R. Pirjola, Geomagnetic storm of 29–31 October 2003: Geomagnetically induced currents and their relation to problems in the Swedish high-voltage power transmission system, *Space Weather*, 3, S08C03, doi:10.1029/2004SW000123, 2005.

Pulkkinen, A., M. Hesse, M. Kuznetsova and Lutz Rastätter, First-principles modeling of geomagnetically induced electromagnetic fields and currents from upstream solar wind to the surface of the Earth, *Annales Geophysicae*, 25, 881-893, 2007a.

Pulkkinen, A., R. Pirjola, and A. Viljanen, Determination of ground conductivity and system parameters for optimal modeling of geomagnetically induced current flow in technological systems”, *Earth, Planets and Space*, 99, 999-1006, 2007b.

Pulkkinen, A., R. Pirjola, and A. Viljanen (2008), Statistics of extreme geomagnetically induced current events, *Space Weather*, 6, S07001, doi:10.1029/2008SW000388, 2008.

Pulkkinen, A., A. Taktakishvili, D. Odstreil and W. Jacobs, Novel approach to geomagnetically induced current forecasts based on remote solar observations, *Space Weather*, 7, S08005, doi:10.1029/2008SW000447, 2009.

Pulkkinen, A., M. Kuznetsova, A. Ridley, J. Raeder, A. Vapirev, D. Weimer, R. Weigel, M. Wiltberger, G. Millward, L. Rastätter, M. Hesse, H. J. Singer and A. Chulaki, Geospace Environment Modeling 2008-2009 Challenge: ground magnetic field perturbations, to submitted to *Space Weather*, 2010.

Smith, C. W., M. H. Acuna, L. F. Burlaga, J. L'Heureux, N. F. Ness and J. Scheifele, The ACE Magnetic Field Experiment, *Space Science Reviews*, 86, 613-632, 1998.

Verification and Validation Report for “Integrated forecasting system for mitigating adverse space weather effects on the Northern American high-voltage power transmission system”, *NASA Applied Sciences Program report*, 2009.

Xie H., L. Ofman, and G. Lawrence, Cone model for halo CMEs: Application to space weather forecasting, *J. Geophys. Res.*, 109, A03109, doi:10.1029/2003JA010226, 2004.

## Appendix A: Solar Shield publications, presentations and EPO activities

### Publications

Pulkkinen, A., M. Hesse, M. Kuznetsova and Lutz Rastätter, First-principles modeling of geomagnetically induced electromagnetic fields and currents from upstream solar wind to the surface of the Earth, *Annales Geophysicae*, 25, 881-893, 2007.

Pulkkinen, A., R. Pirjola, and A. Viljanen, Determination of ground conductivity and system parameters for optimal modeling of geomagnetically induced current flow in technological systems, *Earth, Planets and Space*, 99, 999-1006, 2007.

Pulkkinen, A., R. Pirjola, and A. Viljanen, Statistics of extreme geomagnetically induced current events, *Space Weather*, 6, S07001, doi:10.1029/2008SW000388, 2008.

Pulkkinen, A., and L. Rastätter, Minimum variance analysis-based propagation of the solar wind observations: application to real-time global magnetohydrodynamic simulations, *Space Weather*, 7, S12001, doi:10.1029/2009SW000468, 2009.

Pulkkinen, A., A. Taktakishvili, D. Odstrcil and W. Jacobs, Novel approach to geomagnetically induced current forecasts based on remote solar observations, *Space Weather*, 7, S08005, doi:10.1029/2008SW000447, 2009.

Pulkkinen, A., M. Hesse, S. Habib, L. Van der Zel, B. Damsky, F. Policelli, D. Fugate, and W. Jacobs, Solar Shield: forecasting and mitigating space weather effects on high-voltage power transmission systems, *Natural Hazards*, doi:10.1007/s11069-009-9432-x, 2009.

Pulkkinen, A., A. Viljanen, R. Pirjola, and L. Häkkinen, Electromagnetic source equivalence and extension of the complex image method for geophysical applications, *Progress in Electromagnetics Research B*, 16, 57-84, 2009.

Pulkkinen, A., T. Oates, and A. Taktakishvili, Automatic determination of the conic coronal mass ejection model parameters, *Solar Physics*, doi:10.1007/s11207-009-9473-z, 2009.

Pulkkinen, A., L. Rastätter, M. Kuznetsova, M. Hesse, A. Ridley, J. Raeder, H.J. Singer, and A. Chulaki, Systematic evaluation of ground and geostationary magnetic field predictions generated by global magnetohydrodynamic models, *Journal of Geophysical Research*, 115, A03206, doi:10.1029/2009JA014537, 2010.

Pulkkinen, A. and L. Rastätter, Reply to comment by Haaland et al. on “Minimum variance analysis-based propagation of the solar wind observations: application to real-

time global magnetohydrodynamic simulations”, accepted for publication in *Space Weather*, 2010.

## **Presentations**

Pulkkinen, A., M. Hesse, M. Kuznetsova, and L. Rastaetter, First-principles modeling of geomagnetically induced currents from the upstream solar wind to the surface of the Earth, paper presented at 2006 Fall AGU meeting, San Francisco, CA, December 11-15, 2006.

Policelli, F., and A. Pulkkinen, Space Weather and Applications of NASA Heliospheric Data, paper presented at ISRSE, San Jose, Costa Rica, June 28, 2007

Pulkkinen, A., R. Pirjola, and A. Viljanen, Determination of ground conductivity and system parameters for optimal modeling of geomagnetically induced current flow in technological systems, invited paper presented at IUGG 2007, Perugia, Italy, 2-13 July, 2007.

Pulkkinen, A., R. Pirjola, and A. Viljanen, Statistical coupling between solar wind conditions and extreme geomagnetically induced current events, paper presented at fall AGU 2007, San Francisco, 10–14 December, 2007.

Pulkkinen, A., M. Hesse, M. Kuznetsova, and L. Rastätter, First-principles modeling of geomagnetically induced electromagnetic fields and currents from upstream solar wind to the surface of Earth, invited paper presented at IUGG 2007, Perugia, Italy, 2-13 July, 2007.

Pulkkinen, A., M. Hesse, S. Habib, F. Policelli, M. Kuznetsova, L. Raestatter, B. Damsky, L. Van der Zel, D. Fugate, and W. Jacobs, NASA-EPRI study, invited paper presented at EPRI-SUNBURST 2007, webcast, 12 November, 2007.

Pulkkinen, A., Solar Shield – Forecasting and Mitigating Solar Effects on Power Transmission Systems, invited presentation at NASA Goddard Space Flight Center, UMBC/GEST All Hands Meeting, April 3, 2008.

Pulkkinen, A., M. Hesse, S. Habib, L. Van der Zel, B. Damsky, F. Policelli, D. Fugate and W. Jacobs, Solar Shield – Forecasting and Mitigating Solar Effects on Power Transmission Systems, invited paper presented at Space Weather Workshop, Boulder, CO, April 29 - May 2, 2008.

Damsky, B., Economic Aspects of Space Weather on the Power Grid, invited paper presented at Space Weather Workshop, Boulder, CO, April 29 - May 2, 2008.

Pulkkinen, A., Solar Shield – Forecasting and Mitigating Solar Effects on Power Transmission Systems, invited presentation at University of Maryland, Baltimore County, Physics Department, October 1, 2008.

Pulkkinen, A., M. Hesse, S. Habib, L. Van der Zel, B. Damsky, F. Policelli, D. Fugate and W. Jacobs, Solar Shield – Forecasting and Mitigating Solar Effects on Power Transmission Systems, NASA Goddard Space Flight Center, Heliophysics Science Director's Seminar Series, December 5, 2008.

Pulkkinen, A., L. Rastätter, M. Kuznetsova and A. Chulaki, GEM Challenge 2008: ground magnetic field perturbations, invited paper presented at mini GEM, San Francisco, CA, December 14, 2008.

Pulkkinen, A., N. Buzulukova, L. Rastaetter, M. Kuznetsova, A. Viljanen, and R. Pirjola, First-principles-based modeling of geomagnetically induced currents (GIC) at mid- and low-latitudes, fall AGU, San Francisco, CA, December 15-19, 2008.

Pulkkinen, A., A. Taktakishvili, D. Odstrcil and W. Jacobs, Novel approach to geomagnetically induced current forecasts based on remote solar observations, paper presented at the Space Weather Workshop, Boulder, CO, April 28 - May 1, 2009.

Pulkkinen, A., Geospace models: What works and what does not?, invited presentation at the NASA GSFC Heliophysics Science Division Director's Seminar, August 21, 2009.

Pulkkinen, A., A. Taktakishvili, and T. Oates, Automatic determination of the conic coronal mass ejection model parameters, invited presentation at the George Mason University, Space Weather Laboratory, September 30, 2009.

Pulkkinen, A., M. Hesse, S. Habib, F. Policelli, B. Damsky, L. Van der Zel, D. Fugate, W. Jacobs, Solar Shield – Forecasting and Mitigating Space Weather Effects on High-Voltage Power Transmission Systems, invited presentation at IEEE Seminar Series, TVA, Chattanooga, TN, December 10, 2009.

Pulkkinen, A., A. Taktakishvili, and T. Oates, Automatic determination of the conic coronal mass ejection model parameters, paper presented at the fall AGU, San Francisco, CA, December 14-18, 2009.

Pulkkinen, A., Usage of modern physics-based models in space weather forecasting: current capabilities and future prospects, invited presentation at the Embry-Riddle Aeronautical University, Daytona Beach, FL, February 2, 2010.

Pulkkinen, A., M. Hesse, S. Habib, L. Van der Zel, B. Damsky, F. Policelli, D. Fugate, W. Jacobs and E. Creamer, Solar Shield project - lessons learned and advances made, invited presentation at the Space Weather Workshop, Boulder, CO, April 27-30, 2010.

## **EPO activities**

General public article on the Solar Shield project at [http://www.nasa.gov/topics/solarsystem/features/solar\\_shield.html](http://www.nasa.gov/topics/solarsystem/features/solar_shield.html).

Solar Shield material was prepared for and used in NASA-sponsored Heliophysics Summer School, Boulder, CO, July 23-30, 2008.

Solar Shield material was prepared for and used in NASA Goddard Space Flight Center Visitor Center's Science on Sphere space weather show. A. Pulkkinen presented the show during NASA Launchfest in Sep 13, 2008.

Solar Shield website at [http://ccmc.gsfc.nasa.gov/Solar\\_Shield](http://ccmc.gsfc.nasa.gov/Solar_Shield).

## **Appendix B: Economic Aspects of Space Weather Impact on the High-Voltage Power Transmission Grid**

**Ben L. Damsky**

### **Abstract**

The Solar Shield project is a collaborative effort between the Electric Power Research Institute (EPRI) and NASA, which is now studying the practicality of providing electric utilities with predictions of geomagnetic storms. If this project is to succeed, we must convince first ourselves and then the electric utilities that there will be a benefit from participating.

The basic questions that arise are:

1. What are the losses possible from a major solar storm?
2. What does it cost for a utility to respond to a solar storm alert?
3. How much can utility response lessen the cost of a storm?
4. How accurate must an alert be before it is beneficial for a utility to act on it?

This paper will present estimates for these quantities with the answers divided into the cases of three different levels of solar storm and considered both from the viewpoint of society as a whole and the viewpoint of the electric utility alone.

For storms that are significant, but limited to isolated damage to equipment, the only losses are felt by the electric utility. For a storm, which disrupts power flow to a district, either through grid instability or through damage to multiple transformers, societal losses become many times higher than the equipment and business losses of the power company. A straightforward application of GNP per capita can be used to estimate the total cost.



## **Resilience and Vulnerability of the US Power Grid**

The 48 contiguous states and almost all of Canada are served by three electric power grids, which are termed the Eastern Interconnection, the Western Interconnection and the Texas Interconnection. The dividing line between East and West for this system is near the continental divide. Within each grid, the generators produce power cooperatively and the loads draw power a single pool. This arrangement has the advantage of providing redundancy in the source of power and in the paths the power takes in reaching the various loads.

The power grid has been designed, constructed and operated so as to make a large-scale outage quite remote. While the average customer experiences about 90 minutes of outage per year, this is caused almost entirely by events on the “distribution” portion of the system, the portion devoted to the small scale delivery of moderate amounts of power. The high voltage portion, the “transmission” portion operates under a redundancy rule referred to as “N minus one.” According to this rule, mandated by the North American Electric Reliability Council, or NERC, the loss of any single generation station or any single transmission line will not cause a system collapse. While the rule does allow for collapse when two components are lost, in practice, it generally takes the loss of several components to produce a wide scale outage. To put it differently, even if the loss of two components could take the system down, there are only a few pairs of such critical components for a system with many components. Further, the required practice is that once a critical component fails, the operators should readjust settings within 30 minutes so that the system is once again in an N minus one mode.

The reader should understand that the system is vulnerable to instabilities resulting from sudden shifts because it is necessary to keep the large set of generators operating at the correct phase angle and at precisely the same frequency. Since they are connected together, differences in frequency or proper phase angle cause large flows of circulating power which make it difficult to serve the real load. The point is that having a balance in generation and consumption is necessary, but is not sufficient to insure that no outage occurs.

Within the last twenty years there have been five major transmission outages in the US. The Northridge Earthquake of January 17, 1994 destroyed the southern end of the Pacific DC Intertie and the resulting instability broke apart the Western Interconnection. Later that same year, the loss of a line in Idaho on December 14 began a cascade of circuit trips, which also broke apart the Western grid. In the summer of 1996 there were two further occasions in which the Western Interconnection broke apart during heavy loads and widespread outages occurred. On August 14, 2003 there was a collapse of a major segment of the Eastern Interconnection causing an outage covering Ontario and parts of eight northeast US states. This was the largest outage in US history, depriving 50 million people of electric power. In all of these major cases, the issue was system instability resulting from the sudden loss of multiple transmission lines in quick succession.

The subject of this paper is an economic evaluation of different scenarios associated with solar storms affecting the power grid. An executive overview of the subject event begins with an eruption of material from the sun, a solar storm. (There are several varieties of these storms, but that is not of concern here.) Should this ejected material reach the earth, it is deflected towards the north and south magnetic poles. In the annular “auroral” zones, large currents flow high above the earth and produce auroras in the sky. If the event is small, the affected regions will not extend far from the polar regions. Large events cause the aurora to extend much further towards the equator. In an extreme event, the aurora borealis was seen in Havana, Cuba and Bombay, India.

There are several effects resulting from the phenomenon besides an intriguing night sky show. Of interest to us is the induction of currents within the earth mirroring the currents above the earth. These are termed geomagnetically induced currents or GIC and they can damage or disrupt the grid in a rather short time.

The components in the transmission grid most vulnerable to GIC are the transformers. These devices are designed to handle ac current, but GIC can contain “quasi-dc current” or current that flows in the same direction for seconds or even minutes at one time. When this happens and the current is of significant magnitude (several amperes or more) the transformer core will saturate in one polarity.

The first consequence of this saturation will be significant distortion of the current and voltage waves passing through the transformer. In power parlance, massive amounts of harmonics will flood the system. If these harmonics are sufficiently large and last long enough, they can damage some vulnerable components such as generators and capacitors. They can also cause protective relays to mis-operate from the unexpected signals. Improper trip signals from protective relays can remove lines or compensating components (capacitors or static VAR compensators) from service and thus create a transmission problem.

The second consequence of saturation is that components of the transformer can overheat from the action of magnetic flux that is no longer contained within the core. This can be so severe that copper or steel melts and the transformer can be destroyed. Well before the melting point of metals, the insulation system of a transformer, oil and oil impregnated paper, begins to degrade and then to be destroyed. When the insulation is sufficiently damaged, a short circuit will occur and the resulting arc will focus intense power at the failed location, quickly expanding the damage and causing an explosion if not detected in time.

It is impossible to bypass a transformer, but since there is redundancy in the power grid, the failure of a single transformer should not be a problem for the system. But, by its nature, a GIC event can expose many of the transformers in a significant area to risk of damage or failure at the same time. In reliability studies this is referred to as a “common mode failure.” It is the kind of problem that can defeat redundancy and take down a power grid. For example, the GIC “Halloween Storm” of 2003 caused damage to six large power transformers on the ESKOM grid in South Africa. While the failures were

not immediate during the storm, the damage was traced back to this event. There was also a transformer failure in neighboring Namibia a month later with winding damage that appeared similar to the pattern seen at ESKOM. (7, 11, 13)

Considering the spectrum of GIC events, experience shows us that small “storms” may have no immediate effect, though there may be accelerated aging of transformers from temporary overheating. Somewhat larger storms could only result in damage to one or a few pieces of equipment and only rare storms of the largest magnitude could have catastrophic results. While a power transformer can cost several million dollars, the loss of a transformer is far from the worst outcome from a storm. The most powerful solar storms will affect larger areas and subject them to significant GIC so that there may be a number of transformers lost. The risk is non-linear because the result of losing multiple transformers can be either the collapse of an interconnection or the inability of a utility to serve a significant area. In this case, the cost of the failed transformers becomes a minor part of the societal cost, as will be seen below.

## **Methodology**

In the sections below we will tabulate the significant components of loss or cost associated with three possible scenarios involving solar storms of different magnitudes. Dollar values will be estimated in a transparent manner so the reader can substitute a preferred number or coefficient for a particular case and calculate an alternative total.

These will not be worst case calculations. Instead of choosing the worst, limiting number from the range of possibilities for each factor, we aim to choose a middle number. In case of an actual event, it is likely that some factors will be better than we assume and some will be worse. This is our attempt to estimate a median event and not an attempt to scare the reader with an unlikely, worst case scenario.

## **Possible Losses from a Moderate GIC Event**

Small GIC events, which occur almost every year are of no consequence for the power industry. While some disturbance may be observed on GIC monitors, the system is not affected and the only associated cost comes from modest accelerated aging of transformers. One step up, at the level of a moderate storm, there are some disturbances but no equipment fails. Possible consequences are line trips from mis-operation of protective relays and local overheating in one or more transformers, which results in accelerated aging, referred to as “loss-of-life.” (This term means that the component has undergone degradation that, in the future, will cause its premature failure. For example, a transformer may only last twenty years instead of the expected thirty years because it has experienced a ten year loss-of-life.) It is unlikely that any load will suffer an outage because the transmission system has been built with redundant paths. The cost for a protective relay mis-operation in itself would be the minor cost associated with the engineering investigation to determine definitively what the cause was. The imputed value of loss-of-life for transformers cannot be determined with any precision, but numbers in the range of \$50,000 to \$500,000 per transformer seem plausible. In recent

years the increased use of DGA (dissolved gas analysis of the transformer fluid,) both from hand sampling and from dedicated, continuous monitors, has shown that storms once considered small actually do produce significant dissolved gasses and contribute to loss of transformer life. We will take a conservative value of \$500k as representative of possible long-term costs from a storm at this level. (3, 4, 7, 11, 12)

### **Possible Losses from a Significant GIC Event**

A more powerful storm can destroy a transformer and can cause local loss of power though this may be only for a matter of hours. The cost of a transformer is roughly proportional to its power rating and we are considering those rated from 20 MVA (20,000 kilowatts) to 1000 MVA (1,000,000 kilowatts.) As this is a wide range, we can only attempt an order of magnitude estimate of a representative cost. Utilities typically report that the total cost of installed power equipment is twice the price of the major component after engineering, shipment, auxiliary equipment, foundations and installation are added. We will adopt a nominal value of \$1M for a failed transformer, a cost near the bottom end of the wide range. Additionally, if one transformer completely fails, it is likely that others nearby suffer loss of life so we will take \$ 500K as a representative value for this associated factor. (1, 3, 5, 7, 9, 11, 12, 13, 14, 15, 16)

### **GSU Failure**

Another possible scenario associated with an event of this magnitude is the loss of a generator step up transformer (GSU.) This needs to be considered separately from the loss of a substation transformer because, for the GSU, there is no redundancy in the power path under normal utility practice. Power flows directly from a generator through a GSU and then onto one or more transmission lines. As a consequence, the loss of a GSU removes its attached generation from service until a replacement can be procured and installed. Since large power transformers are custom made and not stocked by either manufacturer or utility, the time to replace a power transformer is at least a year. A practice often adopted is to have a spare at the site for one of the three separate phases, but this single-phase redundancy will not suffice if two or three phases fail at the same time. (1, 3, 5, 9, 12, 16)

The likelihood of GIC damage to a GSU is higher than for a transmission transformer for several reasons. In the first place, some generation is at a remote site dictated by the energy source, a dam or a coal deposit for example. As a consequence, the generation is more likely to be at the far end of a line or at the edge of a grid. Such sites are more prone to GIC currents flowing to ground from the grid. Secondly, GSU transformers are more likely to be operated at or near their power rating. Transmission line transformers must be prepared for contingencies like the loss of a parallel path so they typically operate at something like 50% of their rating, a mode that gives them thermal margin should GIC flow. In contrast, a GSU is often operated at 100% of its rating since there is no possibility of additional power load from any parallel source, GIC not normally being considered. Finally, transformers with separate phases instead of an integrated magnetic circuit are more vulnerable to stray flux.

For a rough estimate of the loss associated with the failure of a GSU, consider the following. If a generating station has a cost of \$500M, an expected rate of return on investment of 10% and is out of service for one year for lack of a GSU, the loss of profit to the utility is \$50M. If we take a simple, linear, 20-year depreciation of the capital cost, this loss is another \$25M. It will be necessary to maintain some of the essential employees on the payroll even though they have no duties since it will be difficult to replace and train a full set when the generation returns on line. If there are forty of these with an average annual cost of \$75k with benefits and overhead, this component will add another \$3M. The cost of the new transformer would add an additional \$1.5M. The utility will need to purchase replacement power on the open market and naturally this will come at the marginal rate rather than the average rate. If we assume the plant operated 350 days a year and averaged 500 MW for ten hours a day and that the differential cost is \$2 per MWhr, then the added cost of replacement power is \$35M. These items total \$115M.

### **Possible Societal Losses from a Major GIC Event**

The most serious outcome from a GIC event is the near simultaneous loss of several transformers in one district so that the transmission system redundancy is overcome and it is impossible to serve an area. There are eight metropolitan areas in the northernmost segment of the 48 contiguous states of the USA, which have more than one million people. (US Census of 2000: area and population in millions: Seattle 3.55; Minneapolis 2.97; Milwaukee 1.69; Grand Rapids 1.09; Detroit 5.46; Buffalo 1.19; Rochester 1.10; Boston 5.82. These average 2.86 million. Including Canada would add six more to the list: Vancouver, Calgary, Edmonton Toronto, Ottawa and Montreal.) This segment, the most vulnerable to GIC geographically, is taken to be north of the line running from New York City through Chicago and on to Portland, Oregon. Extending the limit a few hundred miles further south would add dozens more such areas and would notably add New York City and Chicago to the list. (Two of the three most notable cases of damage from the March 13, 1989 GIC event were south of the line in question. To encompass all three major damage sites from 1989, we would need to set a southern limit at the Mason-Dixon Line.) Consequently, this paper will take as a possible and plausible event the loss of power to an area with a population of one million. If the reader wishes to consider a larger or smaller population area, the scaling will be apparent.

The per capita GNP for the United States has now passed \$44,000 per year or \$170 per working day. If we assume that output is reduced by 80% when electric power is lost, then the cost of an area outage from the point of view of GNP is \$136 per person per day. For a city of one million this comes to \$136M per day or \$680M per week and the cost of a two-week outage is clearly in excess of \$1B.

The US Department of Energy assessed the economic cost of the August 14, 2003 outage as being between \$4.5 and 10 billion. This outage occupied Friday afternoon through Sunday for the most part and affected 50 million people, so, if the simple GNP analysis

suggested above is applied, the cost of losing one working day for this population would be \$6.8 billion which is in good agreement with the government's estimate. (8, 12)

It is important for the reader to understand that the power outage under consideration is in a different class from the ones normally encountered. Almost all of the outages we experience in our daily lives originate from a defect on the distribution system, typically a downed line or a failed distribution transformer. Every utility maintains a stock of overhead and underground cable and distribution transformers (25 KVA is the most common size, units that are familiarly seen on power poles.) An isolated event of this nature is handled in a few hours and often in one hour. The most serious cases at the distribution level involve a large area damaged by an ice storm or a hurricane. Recovery from an ice storm is typically completed in a few days with interim progress bringing customers back on-line every day. Hurricanes can require the longest time for full restoration since it is possible for many distribution poles to be lost as well as lengthy stretches of line. (On the other hand, homes in sections with downed poles are unlikely to be habitable so the loss of power may not be an important concern.) Since the hardware is on hand for these distribution-related outages, the limiting resource is manpower and all utilities already have in place "mutual assistance agreements" with their neighbors to bring in emergency manpower on a short time basis. But the case involving loss of multiple power transformers may not be able to be remedied by application of utility manpower. In the GIC case, the essential items are the power transformers, custom designed and made to order by a handful of manufacturers. Today all large power transformers and many medium sized power transformers are imported into the United States, so even the transportation phase of replacement will consume a month. The Lockheed Martin C-5 Galaxy airplane is rated for a maximum load of 122 tons and might carry a 50 MVA transformer if its profile is low enough. The Russian Antonov AN-225 is rated for a maximum load of 250 tons and might carry a 100 MVA transformer, but only one plane was ever completed. Larger transformers would require ship transport

There are, of course, batteries for some crucial items like the telephone exchange and for cell phone towers, but these are intended to ride through temporary outages and most will be depleted in less than a day, the best ones in a few days. There are also emergency generators for critical locations like hospitals and airports. Experience shows that a significant fraction of these will not function in an emergency. The US average is 5,500 hospital beds per million population with about 275 of these being ICU beds and another 275 being neonatal ICU beds. If we assume that 25% of hospital generators are unable to start the first day of power loss and that 10% of those in ICU beds are vulnerable to the loss of medication requiring electricity, fourteen hospital deaths will result from the GIC caused power outage (12).

The typical fuel storage facility for emergency generation contains a three day supply. There are constraints of space and cost and there is a reasonable wish to limit the possibility of damage from accidental fire. Authorities will be faced with the difficult alternatives of 1) arranging to truck in fuel and operating the hospitals on emergency power or 2) finding alternative beds and evacuating patients to alternative, remote

facilities. A further factor is that emergency generators are typically sold with a warranty for 1000 hours of operation. This suggests that failures can be expected at 2000 hours, less than three months of continuous operation. (12)

It is problematic to calculate the full cost of prolonged loss of power to an entire metropolitan area because there are many aspects of life that are affected. Consider the following factors: Because traffic lights will not operate, traffic control will be difficult and will require manual direction just at a time when the police will be called on for control of looters and for rescue operations. (Looters will soon understand that security cameras and alarm systems are inoperative and that an observer who wants to report a crime lacks a functioning telephone to report to the police.) It is clear that it will be necessary to bring in troops to maintain order and to assist in the logistics of distributing food and water. Regrettably this will add the burden of 10,000 or so additional people who must also be supplied and housed. Clean water must be trucked in since the water will flow only as long as the elevated storage supply lasts. Sewage processing will cease with the loss of power and few cities have capacity for large storage. Gasoline and diesel fuel will be hard to obtain in the metropolitan area because filling stations rely on electric pumps to bring up fuel from underground storage tanks. As was mentioned in the previous paragraph, telephone ground lines and ground relay cell phones (as opposed to satellite based cell phones) will be inoperative after a matter of hours. Computers will be inoperative. Although laptops have batteries and most large installations have a UPS, these have energy storage typically adequate for only a few hours and very seldom for more than a day. Elevators will be inoperative and so apartments on high floors will be untenable, especially for the aged. Grocery stores will have great difficulty handling sales on a manual and cash basis and they will have no refrigeration so the selection of food will be restricted. Milk will probably not be available through conventional distribution modes. With their computers down or unreachable because of telephone outages, banks will be unable to verify current balances and will not disburse cash to depositors and must ship checks outside the effected area for processing. At the same time, merchants who are unable to accept credit or debit cards will insist on the cash that will be so hard to get. (12)

It is impossible to predict in detail what will happen to our model city, but it seems reasonable to assume that all possible resources will be mustered to install portable generators in order to supply critical loads on a piecemeal basis. If we make an arbitrary choice and say that the city is shut down for a quarter of a year, certainly a conservative assumption, the “GNP” loss becomes \$8.84 B and overshadows all other costs for our city.

The system problems associated with our hypothetical storm could also be quite serious. The Northeast blackout of 2003 showed us that the major grids of the US can still be vulnerable to a system disturbance. Sudden losses of lines and associated generation can cause instability and break apart a system even if there is a reasonable match between supply and load. The resulting collapse would leave millions of people without power until the system could be restored. Based on the 2003 event, we might expect 50 million people to experience loss of power for three days. Unlike the one million in the city

whose transformers have been destroyed, these people will be supplied again just as soon as the system can be restored. Another difference is that there is no loss from equipment that has been destroyed. But because the number of affected people is so large, the societal cost is high even for an outage of a few days. If we follow the “GNP analysis” which was applied to the city of one million and assume that two of the three outage days were work days and that 80% of output is lost, then we have 50 million people losing \$272 each for a total cost of \$13.6 B.

So a major GIC storm might produce a long-term outage in a major metropolitan area leaving one million people without power for months and cause a system disturbance that causes an outage of a few days for tens of millions of other people in Canada and the northern half of the US. Adding these two components together gives a total loss of \$22.4 B for the economy.

The level of GIC needed for this major event is not reached in a typical eleven-year solar cycle, but neither would it require such a high flow that we think it impossible. By trying to gauge the GIC level of past storms, which occurred when there was no monitoring, we might conclude that such giant storms only occur with a period of 40 years or so. Even after forty years, if the storm strikes with its peak intensity at 3 AM local time, the power grid will be much less likely to collapse and transformers will have more thermal reserve to withstand the effects of saturation. It is not our intention to claim that such a catastrophe is likely to strike the US in the near future, but it is our point that the possibility over the next several decades is not remote.

### **Possible Utility Losses from a Major GIC Event**

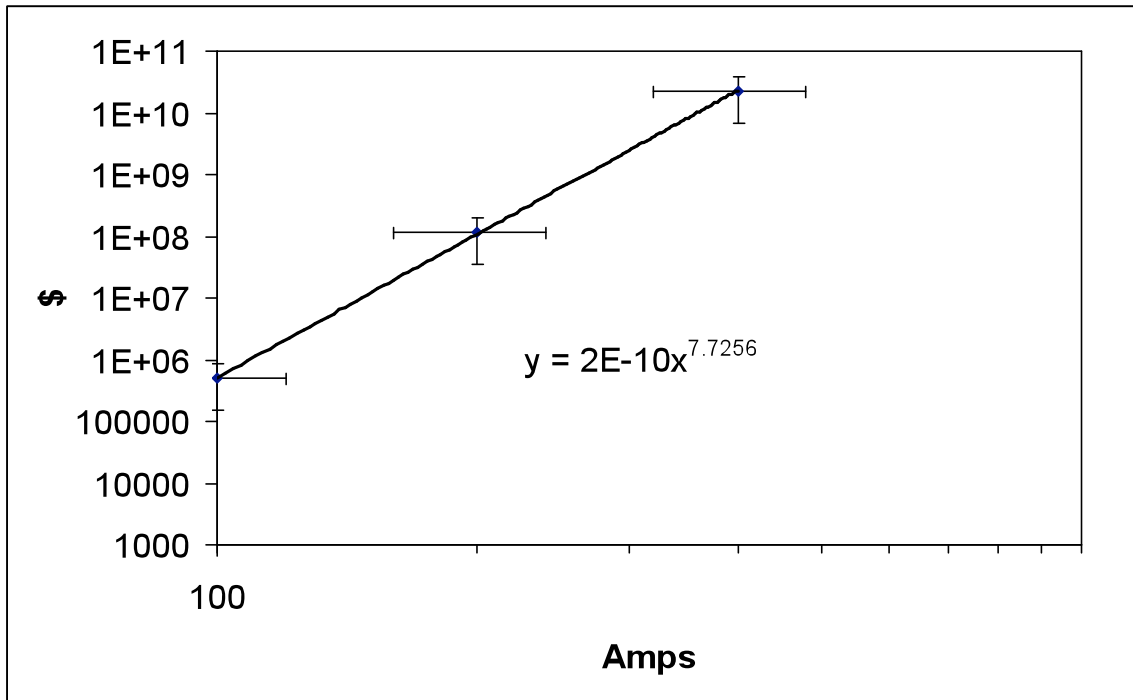
Although major, the losses to the electric utility serving the city of one million are considerably less than the societal losses. On the equipment side we can reasonably assume the loss of 10 power transformers, which would total \$15M.

If we examine the cost to a utility of being unable to serve a city of one million, the following facts come into play: Annual US production of electric power is over 3.5 trillion KWH per year and growing almost 2% annually. Per capita annual consumption is 11,700 KWH. The cost per KWHr is \$.097 (average for the total US in July 2007 according to the website of the DOE Energy Information Agency) so the annual per capita cost is \$1135. Consequently, over a period of a year, an average city of one million consumes electric power costing \$1.14B. Since no fuel will be burned during the outage, we can deduct the cost of this item. A typical proportion for fuel is 30% of the cost of power so the net loss to the utility would be \$794M. Similarly, the utility may be able to furlough some of its employees whose skills are not considered critical. Removing 300 from the payroll with an average cost of \$50K for salary and benefits would further reduce the utility loss by \$15M to \$779M. If we add the cost of the lost transformers and an allowance for additional transformers that have suffered loss of life, the total cost to the utility becomes \$794M.

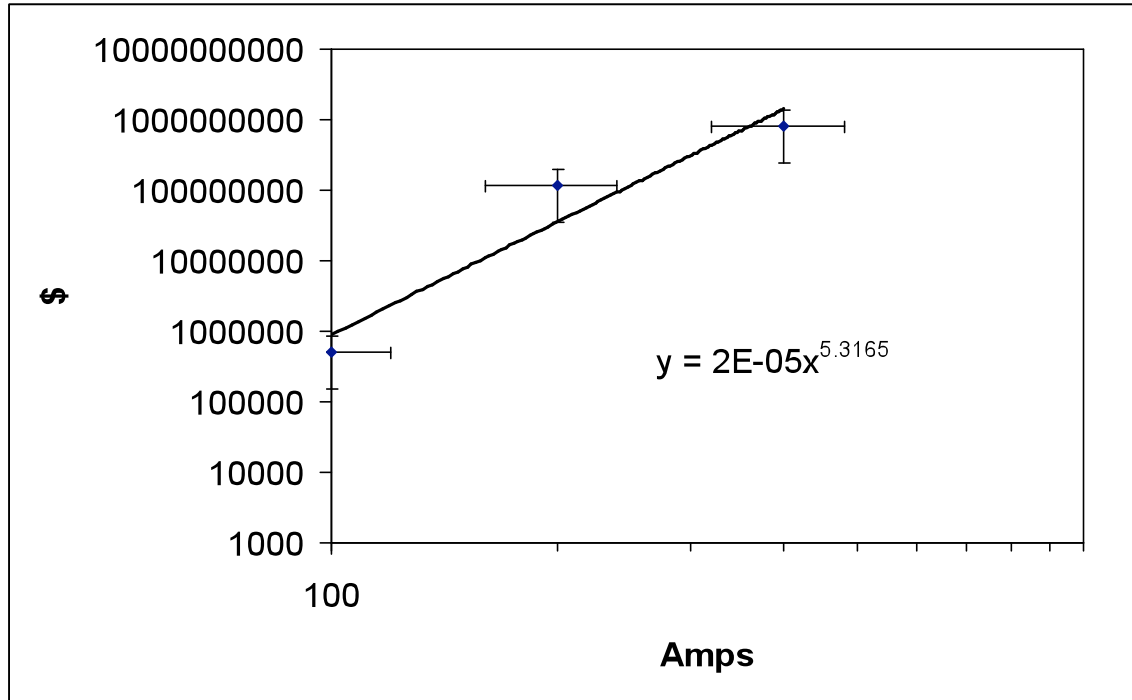


## Table and Plots of Losses

GIC Level	Utility Loss	Societal Loss
100A	500K	500K
200A	115M	115M
400A	794M	22.4B



Plot of Cost to Society (Log – Log axes)



**Plot of Cost to a Model Utility (Log – Log axes)**

### Cost of Response by an Electric Utility to GIC Alert

Balanced against the possible losses which a utility or society as a whole might experience are the costs associated with responding to an alert. We will estimate the cost of the major components of response below. We will assume that the response, and thus the cost, is the same regardless of the level of the storm.

### Cancellation of Preventive Maintenance Work

A recommended practice is to cancel any possible transmission maintenance work during a GIC alert so that all possible lines and generation can be placed in service. It will be difficult if not impossible to assign these workers to alternative tasks during the day-long period we will assume for the alert. The staff assigned to transmission maintenance work is estimated to be 20 and their hourly cost to be \$50, so their cost for the day sums to \$8k. Notice that the relevant staff consists of only those doing transmission maintenance work and does not include those involved in repairs, construction or in distribution field work.

### Deviation from Economic Dispatch

It is a universal practice of utilities to add or reduce generation according to the marginal cost of power from each of the available generators. Thus the generation turned on first is the one, which provides the least expensive power; the second to be added is the one with the next lowest cost of power and so on. When power demand is declining, the first

unit to be turned off is the one with the highest marginal power cost, and so on. This practice is termed “economic dispatch.” Since the capital costs are sunk costs, the overriding consideration determining the ranking of generators is the cost of fuel per KWhr. This can easily vary by a factor of two making it very important to follow economic dispatch.

The recommended practice when a GIC storm is expected is to turn on as many generators as possible and not to have any of them operating at or near their full rating. Any optional import of power should be terminated or minimized to avoid long range power transmission. This would provide as much thermal margin as possible for the associated GSU transformers and would make the utility as flexible as possible should a generator or a line be lost. There is, however, a significant cost associated with such a move. If we assume our model utility is generating 1,500 MW (about what would be typically needed for a service area population of 1 million) and that the differential cost of power from a full generation fleet instead of economic dispatch is \$10 per MWhr, and that the utility operates 20% in a non-economic dispatch mode, then the extra cost of operating in this mode for 10 hours would be \$30K.

### **Total Cost of Response**

The cost of the last two items totals \$38K under our assumptions. This is the response cost that must be justified by the probability of reducing losses when there is a forecast of a major storm. For minor storms, there will be no alert, the utility will take no action and there will be no cost.

### **Savings from Utility Action**

While it is clear that a large solar storm can have horrendous consequences and cost the economy immense amounts, it is not as clear that utility action can prevent this. Actually, it is likely that the effect of the steps that utilities can take will only reduce the GIC by modest amounts. By putting all possible lines and generators in service to spread the load, the GIC might be reduced at any one spot by something like 10 or 20%. These steps will also allow the vulnerable transformers to operate further below their power rating and so run cooler, have a lower flux density in their core and therefore be slightly more resistant to damage from the GIC, something harder to gauge. Transformers with saturated cores consume reactive power and the system will be better able to tolerate this if more generation and lines are available. This will improve the robustness of the grid, making it less likely to collapse.

But the value of these steps can be understood from the extreme slopes shown in figures 1 and 2. Because we expect an exponential shift from changing GIC levels, the benefit from a 20% reduction in GIC is substantial. The graphs, of course, are single exponent approximations of complex phenomena, which will actually involve steps or jumps in the cost as individual components and systems fail. Nevertheless, they represent the best approximation we have of how the costs depend on current levels and they clearly indicate an extremely sharp dependence. Using the exponent 7.7 taken from the plot of

societal cost, one can see that just a 20% reduction in GIC level diminishes the cost to society by a factor of 5. (In mathematical terms,  $0.8^{7.7} = 0.18$ .) Consequently, a generic estimate of the value of utility action is 80% of the expected loss anticipated from the case with no action.

## Net Value of Solar Shield

If we neglect the rare occurrences of larger storms and focus only on the moderate storms, which produce GIC at the 100-Ampere level, we see that the expected savings are \$400k (80% of \$500k.) The estimate of the cost of each response given above was \$38K so the action is beneficial if the alert is correct more than 10% of the time. That is, we can tolerate nine “false alarms” for each accurate prediction and still have a net benefit. It is expected that most of the false alarms will be cases in which the storm produced a lower level of GIC than predicted, 10 amperes instead of 100, for instance. This must be considered a false alarm since the utility would probably take no action if it knew no more than 10 amperes would flow.

EPRI’s SUNBURST Network has ten years of detailed records of GIC at multiple sites on several continents and this gives us some measure of the distribution and frequency of the more common lower level storms. This data is still insufficient for accurate statistics concerning the larger storms since they are so rare. Still, there are non-numerical, historical records from such documented observations as telegraph operator reports and sightings of extremely southern auroras to give us order of magnitude estimates for such major storms as the September 1-2 “Carrington Event” of 1859 (auroras reported from Havana, Cuba and Bombay, India,) the mid February event of 1872 (auroras reported at 19° latitude) and the May 14-15 event of 1921. More recently, the storms of August 1972 and of March 13, 1989 were documented in many ways, though there were still no ongoing GIC measurements. Taken together, these five major storms in a 150-year period suggest that the ratio of 100-Ampere events to 200-Ampere events is probably 3 or 4 to 1 and the ratio of 200-Ampere events to 400-Ampere events is probably similar. (1, 2, 6, 9, 12, 13, 14)

Even if these assumptions are incorrect and the true occurrence ratios are 10 and 10 instead of 4 and 4, the exponential increase in cost for the larger events results in the majority of the expected losses coming from the larger events. Putting this in perspective, savings from the 100-Ampere storms can justify a utility’s preventive actions while the harder-to-quantify savings from larger but rare storms is believed to be even more significant.

## References

(1) Albertson, V D, Bozoki, B, Feero, W E, Kappenman, J G, Larsen, E V, Nordell, D E, Ponder J, Prabhakara, F S, Thompson, K and Walling, R, Geomagnetic disturbance effects on power systems, IEEE Trans on Power Delivery, Vol 8, No 3, July 1992, pages 1206-1216.

- (2) Anderson, C W, Magnetic storms and cable communications, in Kennel, C F, Lanzerotti, L J and Parker, E N, eds, *Solar System Plasma Physics*, (Elsevier, New York 1979,) pages 323-327.
- (3) Aubin, J, Effects of geomagnetically induced currents on power transformers, *Cigre Electra* 141, April 1992, pages 24-33.
- (4) Breckenridge, T H, Cumming T and Merron, J, Geomagnetically Induced Current Detection and Monitoring Developments in Power System Protection, Conference Publication No. 479, IEEE 2001.
- (5) CEA, Magnetic storm blamed for Hydro-Quebec system failure CEA Bulletin April 1989 Reprinted in IEEE Power Engineering Review Vol 9, No 7, July 1989, page 6.
- (6) Clark, S, *The Sun Kings: The Unexpected Tragedy of Richard Carrington and the Tale of How Modern Astronomy Began*, ISBN 978-0-691-12660-9, (Princeton, 2007).
- (7) Gaunt, C.T., and Coetzee. G, Transformer failures in regions incorrectly considered to have low GIC-risk, *Proceedings of Power Tech*, 1-5 July 2007, Lausanne, Switzerland.
- (8) Glotfelty, J, *Electric Reliability: A National Priority*, USDOE report of March 1, 2004.
- (9) Kappenman, J G, Geomagnetic storms and their impact on power systems, *IEEE Power Engineering Review*, May 1996, pages 5-8.
- (10) Koen, J and Gaunt, C T, Disturbances in the Southern African Power Network due to Geomagnetically Induced Currents, *Cigre Session Paper* 36-206, Paris August 2002.
- (11) Koen, J and Gaunt, C T, Geomagnetically Induced Currents at Mid-Latitudes XXVIIth General Assembly of the International Union of Radio Science Maastricht Exhibition and Congress Centre (MECC) Maastricht, the Netherlands, 17-24 August 2002.
- (12) National Research Council, *Severe Space Weather Events – Understanding Societal and Economic Impacts Workshop Report* (2008), ISBN: 0-309-12770-x, Posted on-line at: <http://www.nap.edu/catalog/12507.html>.
- (13) Odenwald, S F and Green, J L, Bracing for a Solar Superstorm, *Scientific American*, August 2008.
- (14) Pulkkinen, A Lindahl, S, Viljanen, A and Porjola, R, Geomagnetic storm of 29-31 October 2003: Geomagnetically induced currents and their relation to problems in the Swedish high-voltage power transmission system, *Space Weather* Vol 3, S08C03 2005.
- (15) Ringlee, R J and Stewart, J R, Geomagnetic Effects on Power Systems, *IEEE Power Engineering Review*, Vol 9, No 7, pages 6-9, July 1989.

(16) Wrubel, J N Monitoring for geomagnetic induced current flow effects using existing EMS telemetering, pages 45 – 49, Conference Proceedings, Power Industry Computer Application Conference, Baltimore, 1991, ISBN: 0-87942-620-9.